OUR COSMIC UNIVERSE

John Kraus

A kaleidoscopic panorama

Great Moments of Discovery
Great Adventures to Come

Foreword by Arno Penzias

To Bob Cooper
with best wishes
John Kraus

Our Cosmic Universe

Other Books by John Kraus

Antennas, (McGraw-Hill, 1950) 28 printings to date.
Japanese language edition, Tokyo, 1953.

Electromagnetics (Mc-Graw-Hill, 1953) 22 printings.
Spanish language edition (El Ateneo, Buenos Aires, 1960).

Electromagnetics 2nd edition with Keith Carver (McGraw-Hill, 1973).
10 printings to date
International edition (McGraw-Hill Kogakusha, Tokyo, 1974).
Portugese language edition (Guanabara Dois, Rio de Janeiro, 1978).
Chinese edition (Southwest Book Co., Taiwan, 1978).

Electromagnetics 3rd edition with Keith Carver (McGraw-Hill, in preparation).

Radio Astronomy (McGraw-Hill, 1966) 10 printings to date.
Russian language edition (Soviet Radio, Moscow, 1973).

Big Ear (Cygnus-Quasar Books, 1976) 4 printings to date.
Japanese language edition (CQ Publishing Co., Tokyo, 1980).

John Kraus is the inventor of the helical antenna, corner reflector antenna, close-spacing arrays and other antenna types. He is designer-builder of the Ohio State University 110-meter radio telescope, a design adopted for a large radio telescope in France and two in Russia, one of which is the world's largest. He is co-discoverer with his students of many unusual celestial objects including prototype erratic variable OJ287, distant quasar OH471 and quasar OQ172, for many years and currently the most distant known object in the universe.

Arno Penzias is best known for the discovery, with Robert W. Wilson, of cosmic microwave background radiation which provides decisive evidence in support of the big-bang theory of the origin of the universe. They shared the 1978 Nobel Prize in Physics for this work. More recently he has been involved in the discovery and study of a number of chemical molecules in space. His current research focuses on how elements in these molecules form.

OUR COSMIC UNIVERSE

by John Kraus

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Foreword

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Foreword

The sky above us has a unique ability to excite our imagination and reward our curiosity. As instruments extend the range of our perception, the list of familiar astronomical objects has grown accordingly. Supernovae, pulsars and black holes now cause us to speak of the births and deaths of the once immutable stars, even of the birth and destiny of the Universe itself.

"Our Cosmic Universe" gives an account of the observations upon which our knowledge of the larger world is based. The style of the presentation is anecdotal with an enjoyable series of human-interest glimpses showing how flashes of insight, gained through the creation and use of new instruments, have enlarged mankind's perception of the electromagnetic spectrum. Some appreciation of the magnitude of this increased breadth can be gained by regarding the spectrum (page 42) in terms of octaves, like the keyboard of some cosmic piano. The visible spectrum, from red to violet, extends over something like a single octave. By contrast, the presently observed range from 10 million electron-volt gamma rays to 1 megahertz radio waves encompasses almost fifty octaves! The component parts of this panoramic window have received disparate amounts of scientific attention for reasons having to do with history, technology, and theoretical interest, among others. Accordingly, optical and radio astronomy are treated at greater length than are other areas.

As the reader's attention is drawn from one topic to another in the book's multi-faceted account, one would do well to keep an underlying framework in mind. An introductory notion of such a framework can be gained from a leisurely stroll over the "Universe in Seven Steps" beginning on page 10.

A good way of bringing disparate images into a common picture is to look for common properties such as rotation. We see rotation in the earth, the sun, pulsars, spiral nebulae and many other objects, for a very good reason. They have all formed by condensation out of larger objects which, like a spinning ice skater who pulls his arms inward, spin faster as their diameter decreases. Rotating objects tend to flatten out in the plane of the centrifugal force resulting from the rotation, bringing to mind a second property, that of shape. Groups of interacting bodies or particles tend to equalize their energies of motion with time. Thus stable, long-lived aggregates such as star clusters tend to have regular, often spherical shapes. Our attention is therefore drawn to irregularly shaped objects which may have been disrupted by the rapid introduction of additional energy. This is often the first clue that something interesting has happened. Since there are only two basic sources of such energy, one governed by the laws of motion and gravity and the other by the laws of nuclear physics, it is usually possible to characterize even the most exotic phenomena in terms of experience gathered in our earth-bound laboratories.

The book's kaleidoscopic panorama of the universe exemplifies what mankind faces in viewing the Cosmos around us. This situation is likened by the author to that of a fancied mayfly at a county fair attempting to glean as much knowledge of human history and condition as the constraints of its brief life and restricted area of movement will permit. Thus, just as the fly must infer the life cycle of man from the number of infants, children, adults, etc. it encounters (avoiding the pitfalls of sampling too near a merry-go-round, rock band or Senior Citizen's booth) we must be able to identify seemingly different phenomena as stages in the evolution of a single object.

Five or six billion years ago an astronomer studying our sun would have seen a diffuse cloud of gas, detectable only by means of 21-centimeter line radiation from the hydrogen atoms within it. Later, as the cloud condensed under gravity, chemical reactions at the higher density allowed various molecules to form which could be detected by means of millimeter wavelength radio and infrared radiation. Still later as the cloud condensed further, increased heating due to the energy released in the collapse made the infrared radiation more prominent. At yet higher temperature and density, nuclear reactions commenced as a new star was born. This new star turns out to be rather uninteresting, except to those nearby. It is not massive enough to become a supernova and neutron star, later attracting attention to itself as a pulsar. Similar stories can be contrived for other classes of objects, but this single example of a star's age-appearance relationship illustrates the idea.

In keeping with the treatment of astronomy as an ongoing, open-ended process, the author does not conclude with a summarizing theoretical abstraction. Instead, we are given a reading list and a number of practical things to do including plans for building our own telescope, a radio telescope in fact! Thus, each of us can aim toward a personal conclusion to this fascinating story.

Arno Penzias

Preface

Astronomy is the oldest of the sciences. Some refer to it as the "Queen of the Sciences". Interwoven with most of the other sciences, it encompasses the whole universe from the tiniest atom or particle to the largest, most majestic galaxy. Astronomy has provided our calendars, set our clocks and been indispensible for navigation and surveying. But it goes far beyond that because the more we learn about other stars the better we understand our sun and its thermonuclear processes which provide the light and heat necessary to sustain life on the earth and the more we learn about our own and other galaxies, their evolution and destiny, the better we understand how the earth evolved and what its fate may be. But perhaps astronomy's greatest significance for us is cultural, broadening our horizons and giving us a cosmic perspective.

"Our Cosmic Universe" aims at a fullness of scope, which extends to the limits of the universe via all the astronomies of gamma ray, x-ray, ultraviolet, optical, infra-red, radio, neutrino, cosmic ray and gravity wave. It is, however, only an introduction, not an encyclopedia, and many references are listed for further reading. Although topics are arranged in chronological or technological sequence, most stand on their own so the book may be opened and read from almost any point.

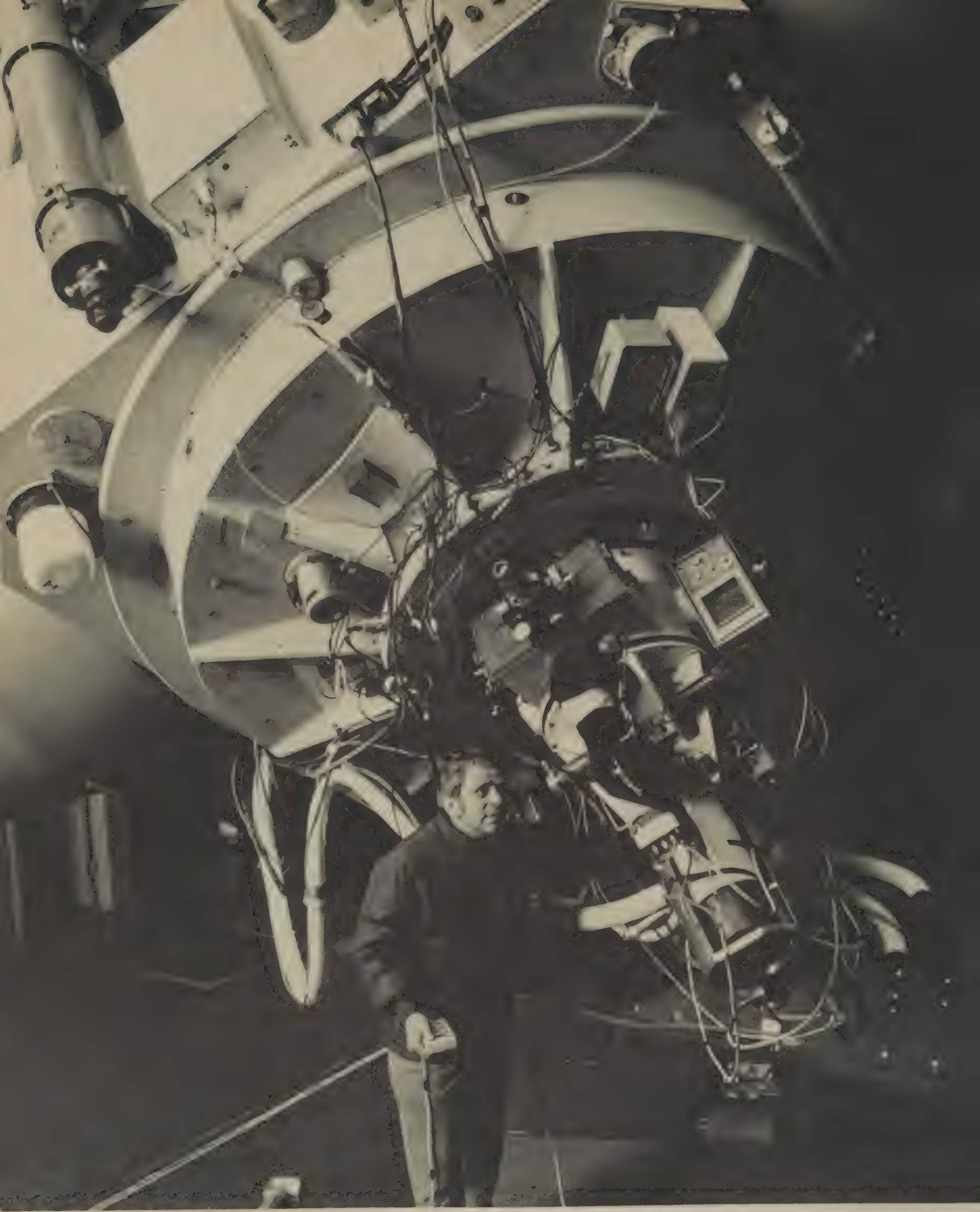
The exploration of the universe is like a climb to the top of Mount Everest. Not accomplished in a single, easy leap, it has been a slow, arduous struggle challenging the abilities and intellects of great numbers of scientists and engineers for hundreds of years. Astronomy is not simply a body of cold facts detached from man. It is a dynamic subject whose meaning and significance are extensions of man. Astronomy is man at his best, straining with his instruments to see, hear and learn, and gain relevance to the cosmos.

The first chapter of the book is an introduction to the universe setting a cosmic perspective. This is followed by chapters on optical, radio and other astronomies with accounts of what we have learned, how we have learned it (the instruments involved) and who made it all come to pass (the individuals and their experiences). Our universe is a great frontier — an exciting frontier — we have only just begun to explore."Our Cosmic Universe" tells about the first optical telescope, the first radio telescope, the discovery of x-rays and cosmic rays, of pulsars and gamma rays from space, and then in the chapter on "Practical Things to Know and Do" describes what persons can do to enrich their knowledge and understanding with simple observations and experiments with small telescopes of modest cost, both optical and radio. Many tables provide a wealth of useful astronomical information.

The book would not have been possible without the assistance and encouragement of many persons, chief of whom is my wife, Alice. Many of my colleagues provided helpful comments and, in particular, I wish to acknowledge those of Dr. Geoffrey Keller, Professor of Astronomy and former Dean of the College of Mathematics and Physical Sciences of the Ohio State University. Dr. Arno Penzias of Bell Laboratories also made many valuable suggestions. The Chinese calligraphy on page 63 was kindly written by Prof. Chen-To Tai of the University of Michigan.

No book is written that does not contain typographical or other inadvertent errors. Readers finding any would do me a great service to call them to my attention so they can be corrected in subsequent printings.

John Kraus



Peter Strittmatter operating the 2.3-meter Steward Observatory telescope on Kitt Peak, Arizona, with which he and Robert Carswell glimpsed "the edge of the universe". The main part of the telescope towers above him with the base supporting the 2.3-meter diameter mirror at the top of the photograph.

INTRODUCTION

Photons from Afar

The stars twinkled brightly through the open dome of the mountain-top observatory. Cold air pouring in chilled Robert Carswell through his jumper suit as he loaded the camera of the big telescope. He was looking for quasars and OH471, the object he was preparing to check, was a radio source suspected of being a quasar, a powerful galaxy so far away that it looks like a star.

As the faint star-like OH471 came into view, Carswell got no hint of it being anything unusual. Nevertheless, he started the 40-minute exposure. Later that night when he developed the photographic plate in the observatory darkroom, he was disappointed to find that it was out-of-focus. Yet he could discern two broad lines in the spectrum like those of a quasar with a big redshift!

He discussed matters with Peter Strittmatter, his observing partner. They agreed it was important to obtain another plate but it was now too late, OH471 was setting in the west, so they decided to try again the following night. This time the plate was sharp and clear and from the lines in the spectrum they estimated the redshift for OH471 at 340 percent, the highest ever measured and the first over 300 percent. This redshift meant that the wavelengths of the lines were increased, or shifted to longer, redder wavelengths, by several times what they are on the earth.

Carswell and Strittmatter were elated, but could they really believe it? To be certain, they needed to confirm some of the fainter lines of the spectrum. This would require another even better plate but their next scheduled time on the telescope was weeks away. So they begged an hour on the telescope a few nights later and obtained a plate confirming their redshift of 340 percent.

CAMBRIDGE UNIVERSITY

Robert Carswell.

They wrote up their results and sent them off for publication in *Nature,* the international journal of science published in London. Some weeks later their article appeared and concurrently the story burst forth from the front page of the Sunday *New York Times* of April ninth, 1973.

In an article about "Seeing the Edge of the Universe," Walter Sullivan, the *Times* Science Editor, explained that the redshift of 340 percent which Carswell and Strittmatter had measured for OH471 meant that it was the most rapidly receding, most powerful and most distant known object in the universe! Its enormous velocity, 90 percent that of light, put it 90 percent of the way to the edge of the universe, at a distance for which the light travel time was more than 12 billion years! A few days later, *Time* magazine referred to OH471 as "the blaze marking the edge of the universe."*

What a contrast to the myopic view of ancient man who scanned the heavens with unaided eye. His sky was close at hand, with sun, moon, planets, and nearby stars. A leap from this to the edge of the universe boggles the mind.

---

* OH471 is a radio source discovered in the Ohio State University sky survey at 21 centimeters wavelength. The "O" stands for Ohio and the H471 is a celestial zip code indicating its location in the sky.

The **redshift** is a number which relates to the distance. The bigger the redshift, the greater the distance. (See later section on the Doppler effect and the redshift).

The term "edge" of the universe is metaphorical. More properly it is a celestial horizon or observable limit.

From Ancient to Modern Astronomy

How had this change come about? It came gradually over the centuries through the insights and efforts of many persons. In the second century A.D., Claudius Ptolemy of Alexandria, Egypt, studied the refraction or bending of light as it passes from one substance to another. In the tenth century A.D., the Arabian Ibn al-Hazen studied the action of a lens and a curved mirror and explained how magnification takes place. But several centuries more passed before these optical principles were applied by Galileo in the first astronomical telescope in 1609.

Galileo was then a 45 year old university professor at Padua, Italy, where a rumor had reached him of a "spy glass" made in Holland. With no other information than that the "glass" made distant objects appear closer, Galileo realized that it must depend on the laws of refraction.

Hurrying to his workshop, he succeeded a few days later in constructing a double-lens spy-glass much superior to the Dutch one he had never seen.

He soon built a better one, then a third, a fourth and a fifth. The newer versions incorporated improvements with the lenses he ground held by cylindrical tubes which slid in and out to facilitate focusing. With his fifth telescope he discovered the moons of Jupiter on January 7, 1610.

With this telescope and others he built, Galileo embarked on a spec-

Galileo and his telescope.

William Herschel, tireless observer, discoverer of Uranus. Herschel, a musician turned astronomer, built and used huge telescopes.

tacular series of further discoveries: mountains on the moon, Saturn's rings, the phases of Venus, spots on the sun's disc, and, noting that they moved, he deduced that the sun rotated. He also resolved the nebulous patches of the Milky Way into myriads of individual stars.

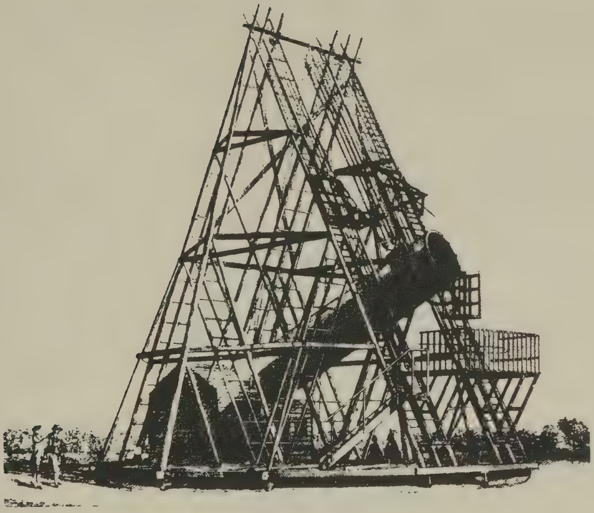
Galileo the experimenter, the innovator, the observer had seen wonders which " . . . infinitely amaze me. Therefore, do I give thanks to God who has been pleased to make me the first observer of marvelous things unrevealed to bygone ages."

Galileo launched man on his first telescope-assisted steps to fathom the cosmos. Other earth-dwellers, such as the big dark-adapted owls, with visual acuity vastly superior to man's, may well have seen some of the marvels revealed to Galileo by his telescope but they have not shared these secrets with man.

In 1773, one hundred and sixty three years after Galileo discovered the moons of Jupiter, a 35-year-old Somersetshire, England, musician named William Herschel became entranced and fascinated with a newly purchased astronomy book that was destined to change his life and the course of astronomy.

Born in Germany, Herschel had joined an army band at the early age of 14. Five years later he emigrated to England where he found work as a musician — an oboe player, violinist, organist and composer of symphonies.

The book so whetted his desire to observe the heavens that within some months he began to build telescopes. Eventually he was producing the biggest and best of his time with mirrors 0.3, 0.8 and even 1.2 meters in diameter mounted in enormous cylindrical tubes up to 12 meters long. Posi-

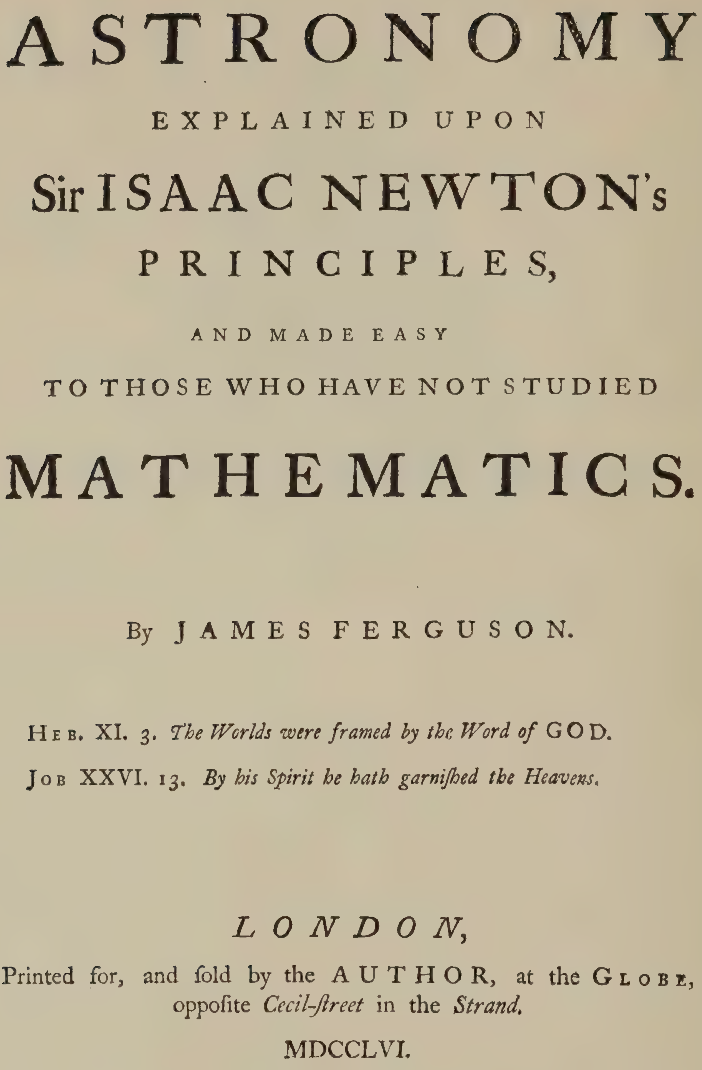


William Herschel's huge howitzer-like telescope which he completed in 1789. It was the largest of its time, and even today is exceeded in size by only a few telescopes.

tioned with block and tackle from huge wooden towers, some of Herschel's telescopes resembled a giant howitzer or a big Bertha jutting out from a wooden barricade. He cast the mirrors out of molten speculum metal (a brilliant copper-tin alloy) and then ground and polished the cooled discs to a parabolic shape. He described the stellar and planetary images he obtained with his telescopes as sharp and "round as a button," testimony to the accuracy of his parabolic mirrors. An irregular mirror surface would have produced blurred, elongated images.

Eight years after he purchased the book he discovered the planet Uranus. He saw at once that it had a disc — stars show only a point of light. He measured its diameter and after a few nights confirmed that it moved against the stellar background the way planets do. His discovery of Uranus created a tremendous sensation and the same year he was appointed astronomer to the court of King George III. With his sister Caroline and in his later years with his son, John, he discovered thousands of nebulas, pondered the shape and extent of our galaxy and its evolution. He discovered the motion of close double stars around each other, extending gravitation and Newton's laws to the realm of the stars.

An indefatigable observer, he sat glued to the eyepiece of his telescope night after night searching the sky systematically for new and unusual objects. Approaching 80, he was still active and enthusiastic with a modest, kind, charming manner, answering any questions about his observations with a boyish earnestness.



ASTRONOMY
EXPLAINED UPON
Sir ISAAC NEWTON's
PRINCIPLES,
AND MADE EASY
TO THOSE WHO HAVE NOT STUDIED
MATHEMATICS.

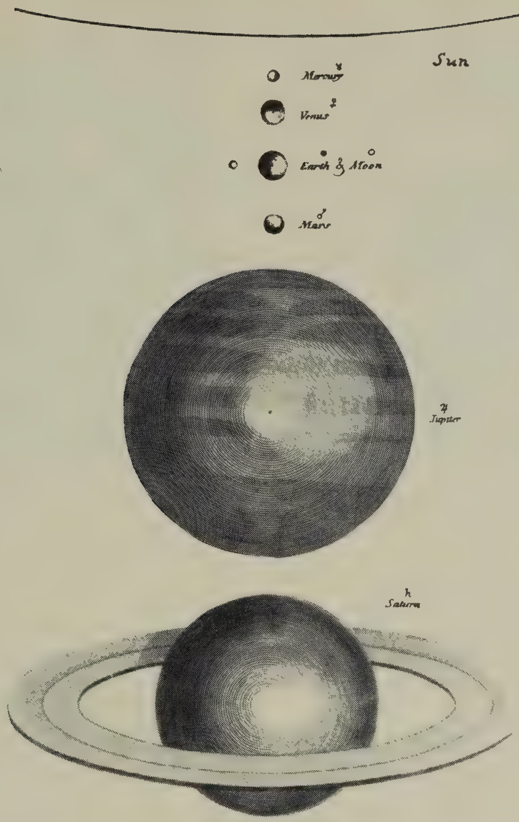
By JAMES FERGUSON.

HEB. XI. 3. *The Worlds were framed by the Word of* GOD.
JOB XXVI. 13. *By his Spirit he hath garniſhed the Heavens.*

LONDON,
Printed for, and ſold by the AUTHOR, at the GLOBE,
oppoſite *Cecil-ſtreet* in the *Strand.*
MDCCLVI.

Title page of the book which turned Herschel from music to the stars and changed the course of astronomy. Printed in London in 1756 it is a very practical book with many excellent drawings by the author. Quoting from the first paragraph:

“Of all the sciences cultivated by mankind, astronomy is acknowledged to be the most sublime, the most interesting and the most useful. Our very faculties are enlarged and our minds exalted with the grandeur of the ideas it conveys.”



Relative sizes of the earth and its moon, Mercury, Venus, Mars, Jupiter and Saturn from Ferguson's book published in 1756. These were the only planets known at that time.

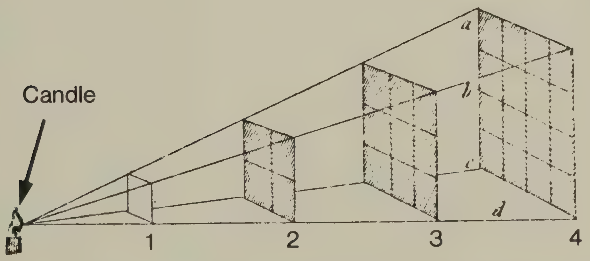


Figure from Ferguson's book illustrating how the light or radiant energy per unit area decreases as the square of the distance. Thus, all of the light passing through the square at unit distance (1) is spread over 4 squares at two times the distance, 9 squares at 3 times the distance and 16 squares at 4 times the distance.

AMERICAN INSTITUTE OF PHYSICS

Harlow Shapley of Harvard.

MICHIGAN HISTORICAL COLLECTIONS

Heber Curtis of the Lick Observatory and later the University of Michigan.

Herschel carried on in the tradition of Galileo as a telescope builder and observer, stretching man's awareness to the stars and nebulas of our galaxy and beyond. Herschel was the father of modern observational astronomy.

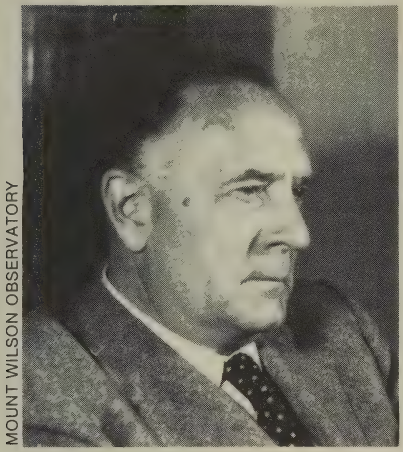
By the mid-1800s Lord Rosse in Ireland had built even larger telescopes, one with a 1.8 meter diameter in a 15 meter long tube. Later William Huggins of England added a spectroscope and also a camera to his telescope.

The spectroscope separated the light from a star into its colors from which the star's composition and its velocity of motion and rotation could be deduced, while the camera provided a permanent record for study; no longer was it necessary to rely on visual impressions.

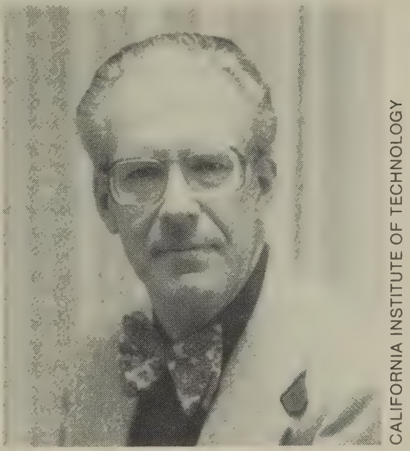
But it was still unclear whether the spiral nebulas which Herschel, Lord Rosse and others had seen were inside or outside our galaxy. Harlow Shapley of Harvard and Heber Curtis of Lick Observatory, California, met before the National Academy of Sciences in 1920 to argue the evidence.

Later Edwin Hubble, lawyer turned astronomer, photographed numerous spiral-shaped nebulas with the 2.5 meter Mt. Wilson, California, telescope and concluded that they were not only galaxies like our own far outside it but were receding, rushing away from us, at velocities which increased with their distance. Thus was born the concept of an expanding universe.

Hubble had hardly announced his amazing results in 1930 when Karl Jansky, with a merry-go-round antenna he built in New Jersey, found that radio waves a million times longer than light were coming to us from the center of our galaxy! Man now had another region of the electromagnetic spectrum for observing the heavens — the centuries-old optical astronomy was supplemented by radio astronomy. Soon Grote Reber of Wheaton, Il-


MOUNT WILSON OBSERVATORY

Edwin Hubble, father of the expanding universe idea.


CALIFORNIA INSTITUTE OF TECHNOLOGY

Maarten Schmidt of Palomar.

linois, was making maps of this radio emission from the sky with a 9-meter diameter parabolic dish antenna, a forerunner and prototype of the modern radio telescope.

After World War II more radio telescopes were built revealing many sources of radio emission in the sky. Some sources corresponded in position to galaxies but others to star-like points of light, which, however, were not stars because their spectra were different from stars. The name **quasar** (for **quasi-stellar** object) was coined to describe them.

The riddle of the quasars was solved by Maarten Schmidt, a young astronomer at Mt. Palomar. From spectra he photographed with the 5-meter telescope, Schmidt demonstrated that the spectrum of the radio source 3C273 could be explained on the basis of an unprecidentedly high redshift of 16 percent, many times greater than the largest redshifts Hubble had measured.

Assuming an expanding universe, 3C273 was at a distance of two billion light years, a tremendous leap into the depths of the cosmos. Although a galaxy of perhaps millions of stars, it was so far away and so compact that it looked like a star. Soon quasars with higher redshifts, implying greater distances, were found but some astronomers thought that redshifts over 300 percent would never be observed because there would be too much absorption of the light over the enormous distances involved. However, in 1973, as already related, Carswell and Strittmatter announced a redshift of 340 percent for OH471 placing it at a distance of nearly 14 billion light years or 90 percent of the way to the ''edge'' of the universe! Man had taken another big step in probing the ultimate depths of the cosmos.

From the unaided eye to Galileo's telescope, to bigger optical telescopes and radio telescopes of yet greater size, man had extended his vision and senses far beyond the sun, moon and planets to the stars of our galaxy and to distant quasars in the most remote reaches of the universe. And in recent years, with orbiting telescopes, the electromagnetic spectrum from gamma and x-rays to long radio waves has been opened to view providing an *all-wavelength* or *full-spectrum astronomy.* We will consider such topics in more detail later on. But first let us journey across the universe to help give us a cosmic perspective.

The Universe in Seven Steps

We live in a vast and mysterious universe. We are gradually learning something of its enormous size and of the rich variety of objects it contains. By way of introduction let us take a brief excursion across it.

The earth is a spinning sphere or planet which, with eight other planets, revolves around a star we call the sun. Beyond the sun and its planets are other stars, the nearest of which is more than 4 light-years away. That is, it is so far it takes light, traveling 300,000 kilometers per second, more than 4 years to travel the distance. The sun and 100 billion other stars constitute our galaxy, a huge flat, disc-like aggregation of stars turning like a great wheel in space. Beyond our galaxy are 100 billion other galaxies which fill our universe.

The distances are so great and so far beyond our realm of ordinary experience as to defy comprehension. We can write the numbers but what do they mean? To try to impart something of the size let us make a change in scale. For example, let us consider that the earth (13,000 kilometers in diameter) is reduced to the size of a pea (6 millimeters). On this new scale the sun is about twice the diameter of a basketball at a distance of 70 paces. The next nearest star is another such basketball an earth's diameter away. Our galaxy is 25,000 times greater in diameter than this distance and the observable universe is something like 100,000 times greater than that.

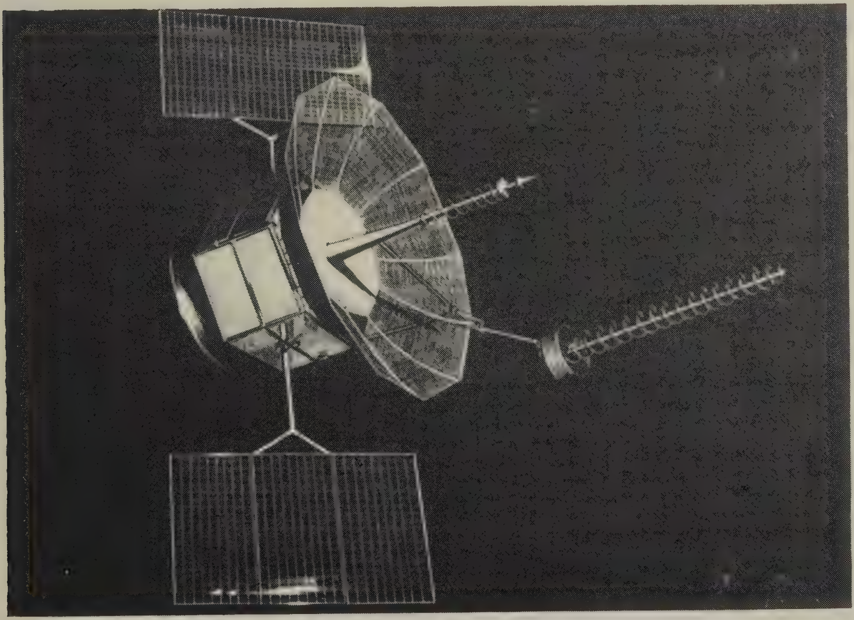
With this brief overview in mind let us go back and take the trip in a more leisurely fashion, this time in seven steps.

THE EARTH AND ITS RINGS

Step 1. The Earth and Its Rings. The earth is surrounded by an atmosphere and above it a region of charged particles called the *ionosphere* and, external to the ionosphere, at least four rings of charged particles.

The earth's magnetism or magnetic field tends to trap many of the rapidly-moving charged particles (mostly electrons and protons) that flow out from the sun with the *solar wind.* These trapped particles form two doughnut-shaped belts or rings around the earth which were discovered by James Van Allen of the University of Iowa using particle counters carried into orbit early in 1958 on Explorer I, the first U.S. satellite. Although the rings are not visible, their presence is manifest in other ways: probes passing through them readily detect their charged particles.

The inner Van Allen ring is about 2500 kilometers and the outer Van Allen ring about 15000 kilometers above the earth's equator. Regions



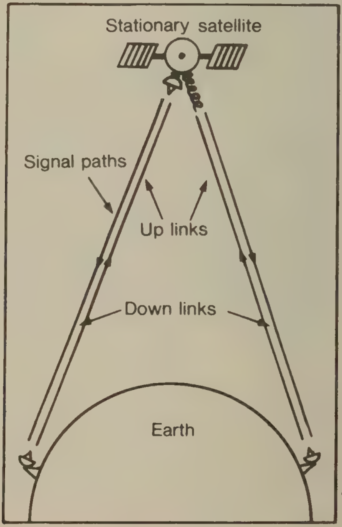
Communication satellite with antennas for gathering in voice, television and data signals from many locations world-wide, including ships and aircraft, and relaying them back to other places. Four such satellites in stationary orbit give global coverage. (Courtesy of TRW Corp.)

over the earth's poles are relatively free from these trapped particles. Since the particles are traveling rapidly, they can be damaging to space vehicles and dangerous to astronauts.

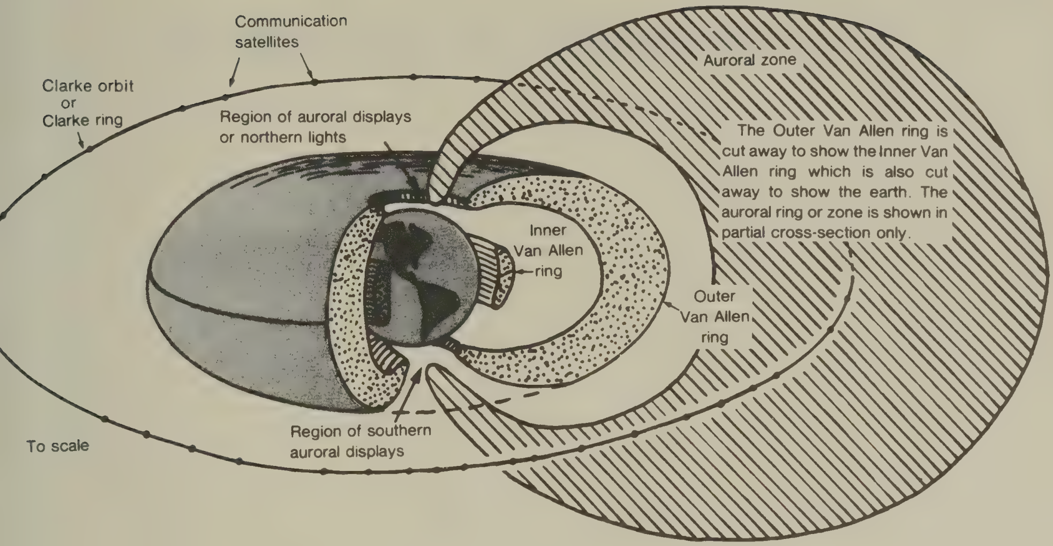
In 1945, while a radar officer in the Royal Air Force, Arthur C. Clarke published an article in *Wireless World* in which he proposed the use of artificial satellites and, in particular, those in a geostationary orbit, as a solution to the world communication problem. This was in the pre-Sputnik era and such a proposal then seemed highly visionary. Yet 12 years later Sputnik went up and only 6 years after that, in 1963, the first successful geostationary satellite, Syncom 2, was put into orbit, and Clarke's proposal became a reality. Now there are many such satellites forming a Clarke ring around the earth at a height of 36000 kilometers above the equator with more satellites being added at frequent intervals.

Farthest out, at heights of as much as 65000 kilometers above the equator, is a great auroral ring or zone enveloping the earth like a huge dune-buggy tire. As with the Van Allen rings, this ring consists of particles trapped in the earth's magnetic field. At the inner cusps of this ring, near the polar regions of the earth, the particles from this ring sometimes enter the earth's upper atmosphere producing the often-spectacular *auroral displays.*

There are many communication satellites in the Clarke ring and the number is increasing. These satellites move with the earth as though attached to it so that from the earth each appears to remain stationary above a fixed point on the equator, hence the name *earth-* or *geo-*



The Earth's Rings


Communication satellites
Clarke orbit or Clarke ring
Region of auroral displays or northern lights
Auroral zone
The Outer Van Allen ring is cut away to show the Inner Van Allen ring which is also cut away to show the earth. The auroral ring or zone is shown in partial cross-section only.
Inner Van Allen ring
Outer Van Allen ring
To scale
Region of southern auroral displays

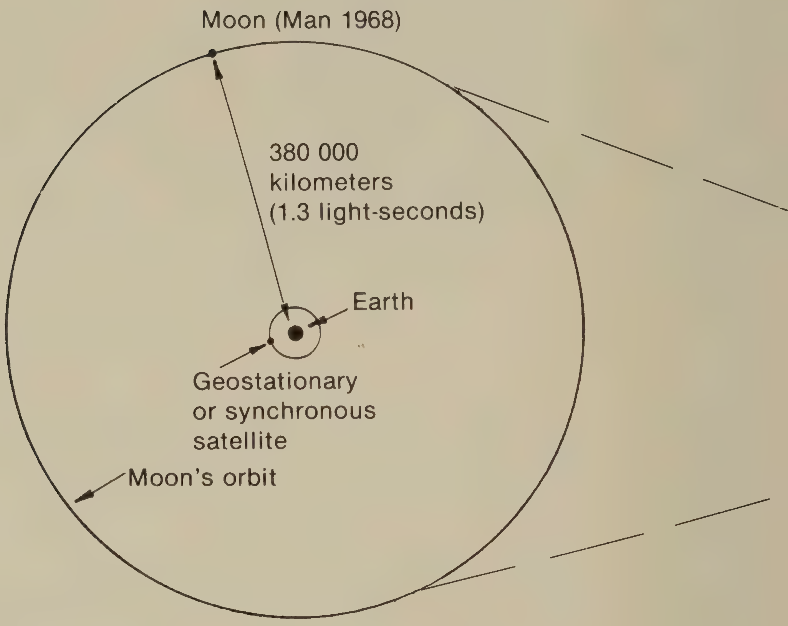
stationary satellite. Still nearer are other man-made satellites travelling around the earth in less than a day down to those skimming the top of the earth's atmosphere and orbiting the earth every 90 minutes.

Communication Via Geostationary Satellite.

A satellite at a height of a few hundred kilometers, just above the atmosphere, orbits the earth in 90 minutes. Further out, a satellite takes longer, the moon requiring one month. At an intermediate height of 36 000 kilometers a satellite goes around in 24 hours, in step with the earth's rotation.

The satellite moves with the earth as though attached to it so that it remains directly above the same point on the equator. Typically, a ground station beams speech, music, TV and data to the satellite which amplifies the signals and beams them back on a different wavelength to a ground station at a remote point where the signal is again amplified and relayed by conventional radio links or cable to its destination. At the same time, signals from the remote station travel in the reverse direction so that two-way communication is possible, but it is not instantaneous. The path between ground stations via satellite is at least 70000 kilometers so that when you talk via satellite there is a one-quarter second delay before what you say reaches your listener at the other end. The delay results from the finite speed of the radio waves (300 000 kilometers per second). Yet such delays are insignificant compared to those of 14 billion years for the radio waves from the quasar OQ172.

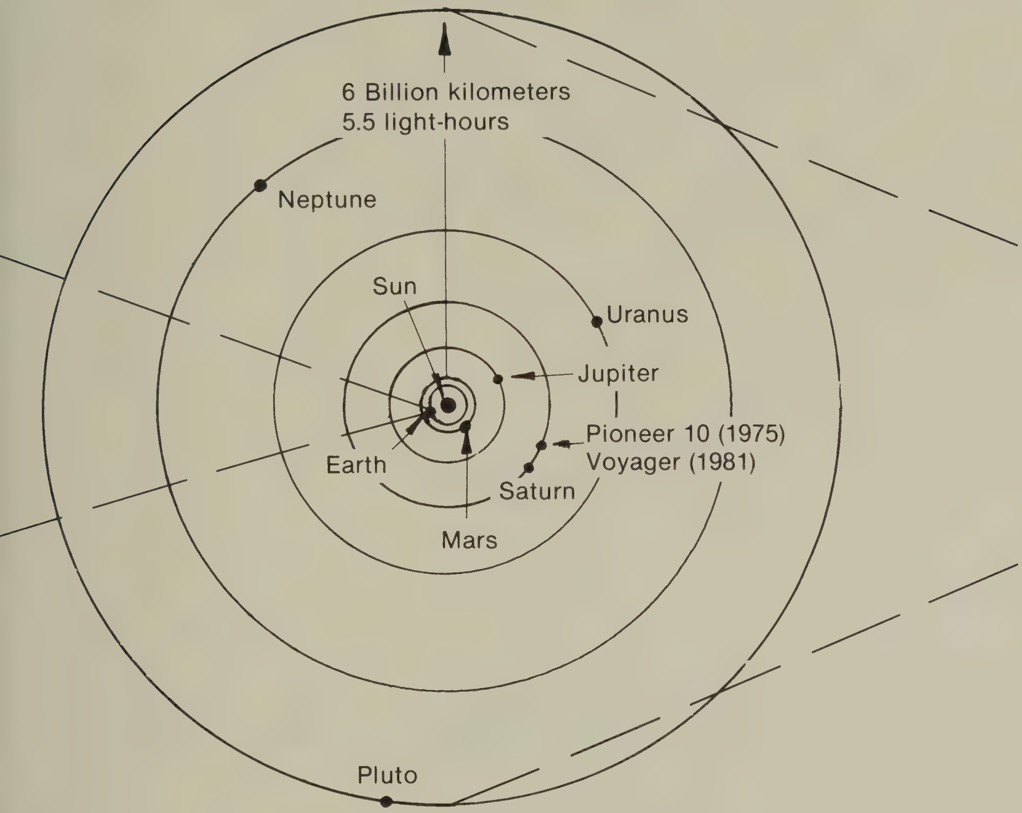
THE EARTH-MOON SYSTEM



Step 2. The Earth-Moon System. Light or radio waves can travel the distance to the moon in about one second. This is the distance reached by manned exploration.

Closer to the earth (at about 36 000 kilometers) are the man-made synchronous satellites travelling around the earth once per day, staying fixed or synchronized above a point on the earth's equator as explained in Step 1.

THE SOLAR SYSTEM

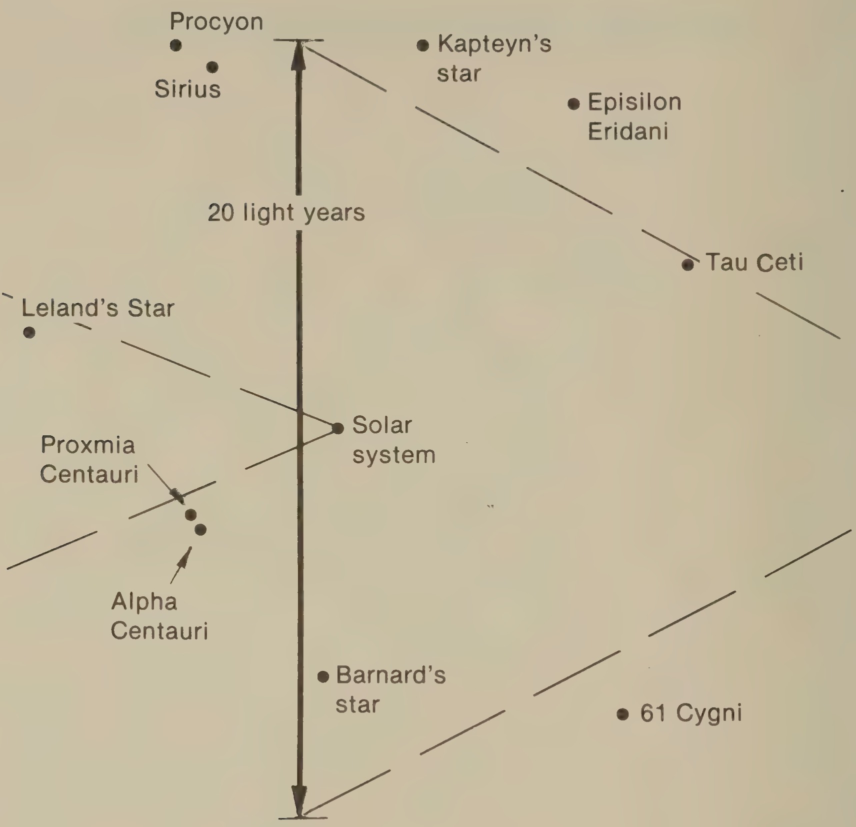


Step 3. The Solar System. The sun, its nine major planets and 1000s of minor planets or asteroids constitute the solar system. The sun is a nuclear-powered star about one and one-half million kilometers in diameter. It is 6 billion kilometers from the sun to the outermost planet, Pluto. Light or other electromagnetic waves travel this distance in 5½ hours. The earth-moon system is relatively close to the sun at a distance light traverses in 8 minutes.

Unmanned probes have penetrated to the orbit of Saturn or one-third of the way to Pluto. The earth-moon system of Step 2 must be reduced by a factor of 10 000 to correspond to the scale of the solar system (Step 3).

The dots showing the sun, earth and other planets are relatively too large. To represent their proper sizes they should be at least 100 times smaller in diameter.

THE SOLAR NEIGHBORHOOD

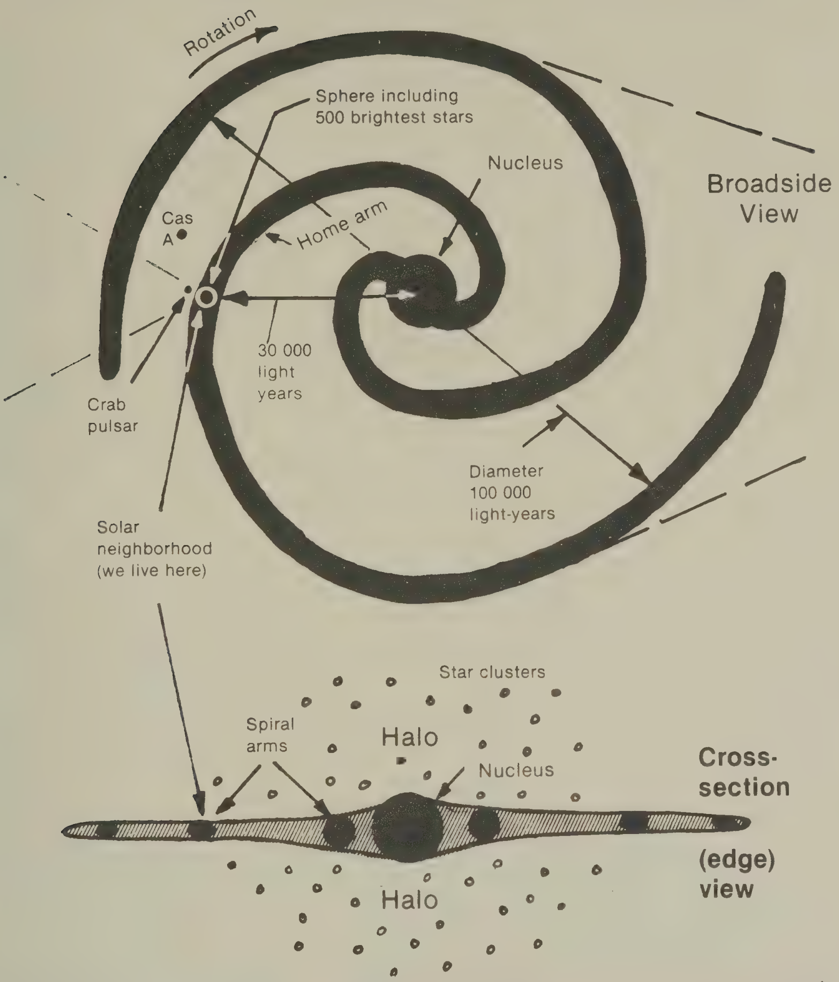


Step 4. The Solar Neighborhood. The sun and some of the closer stars form the solar neighborhood. There are a dozen stars closer than about 10 light-years, the nearest being about 4 light-years; however, with the exception of Sirius, Alpha Centauri and Procyon, they are too faint to be seen with the unaided eye.

The solar system must be reduced by a factor of 17 000 from the Step 3 diagram to be the correct size in the solar neighborhood diagram. The dot for the solar system (diameter equal to Pluto's orbit) should be at least 1000 times smaller, while the star dots are a million times too big.

OUR GALAXY

Idealized

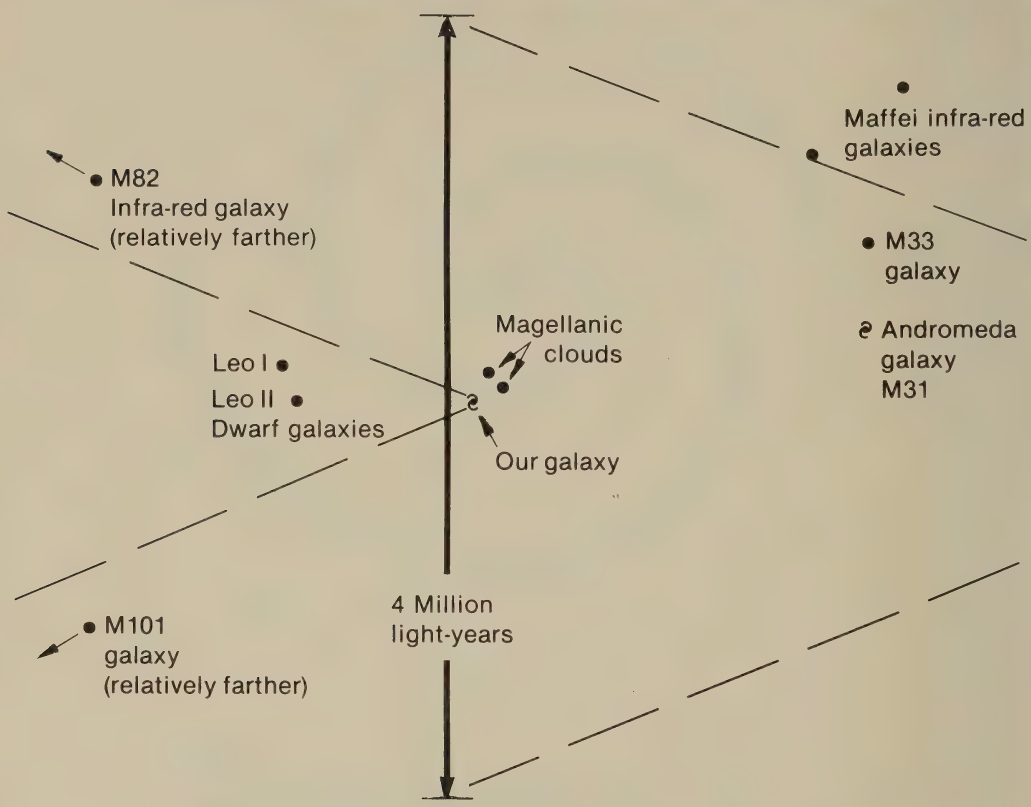


Step 5. Our Galaxy. The sun with 100 billion other stars form a huge aggregation called our galaxy (or Milky Way system), a flattened disc 100 000 light years in diameter turning like a great wheel once in 300 million years. The sketches show it as seen broadside and edge-on. In the nucleus at its center and in the long trailing spiral arms the stars are closer together than between the arms.

Surrounding the disc, like a swarm of bees, are a few hundred star clusters and a sprinkling of individual stars. These clusters and stars form a *galactic halo,* a spherical region centered on the nucleus. Some of the clusters may contain as many as 100 000 stars or more.

The solar system where we live is in a spiral arm about two-thirds of the way to the edge (30 000 light-years from the center). Most of the 500 brightest stars in the sky are relatively close (within 1000 light-years). The Crab pulsar and Cassiopeia A (Cas A) are further from the solar neighborhood. (Continued on next page).

THE GALACTIC NEIGHBORHOOD



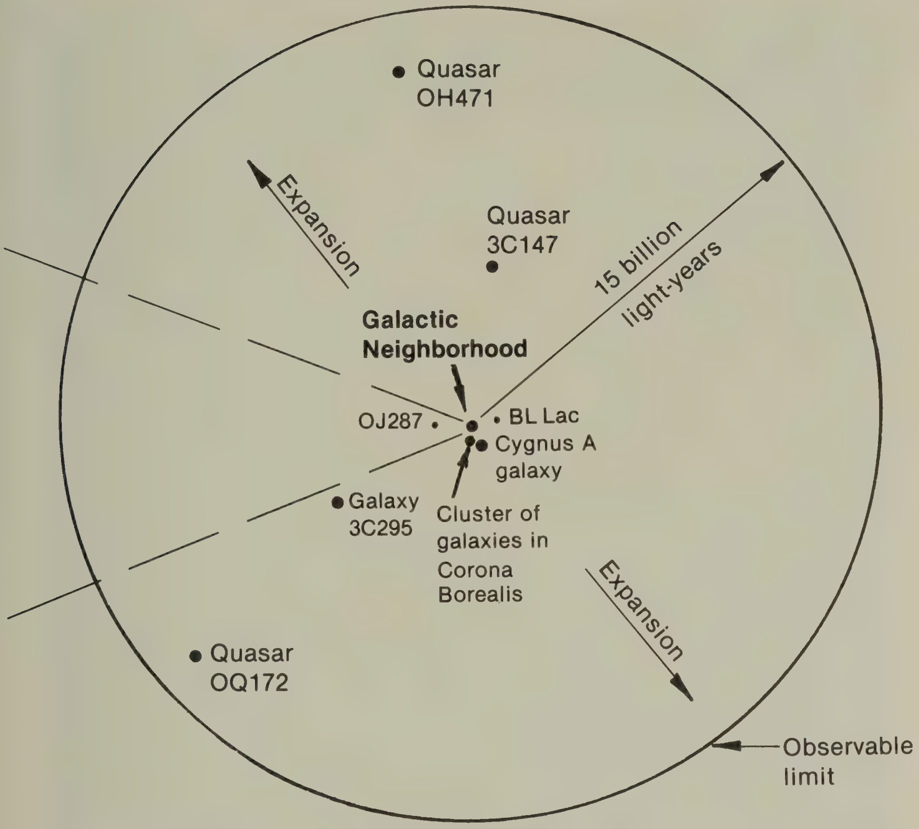
Step 6. The Galactic Neighborhood. Our galaxy and some nearby galaxies such as the Magellanic clouds and the Andromeda galaxy form the galactic neighborhood.

Our galaxy sketch must be reduced by a factor of 40 from the Step 5 diagram to be the correct size on the galactic neighborhood diagram. Our galaxy and the other galaxies are approximately the proper relative size.

(Step 5 continued)

The solar neighborhood sketch must be reduced by a factor of 5000 from the Step 4 diagram to be the correct size on the galaxy diagram. The dot showing the sola neighborhood should be about 100 times smaller in diameter to indicate its proper relative size. The sketch is idealized. See page 101 for a map of the hydrogen distribution in ou galaxy which more accurately delineates the spiral arms.

THE UNIVERSE



Step 7. The Universe. The known universe contains our galaxy and 100 billion other galaxies out to a celestial horizon or observable limit at a radius of 15 billion light years. The other galaxies seem to be moving away as though the universe were expanding, the recession velocity increasing with the distance.

The galactic neighborhood is shown at the center with a few radio galaxies such as Cygnus A and 3C295 at increasing distances. The most distant known object, quasar OQ172, is receding at 91 percent of the velocity of light.

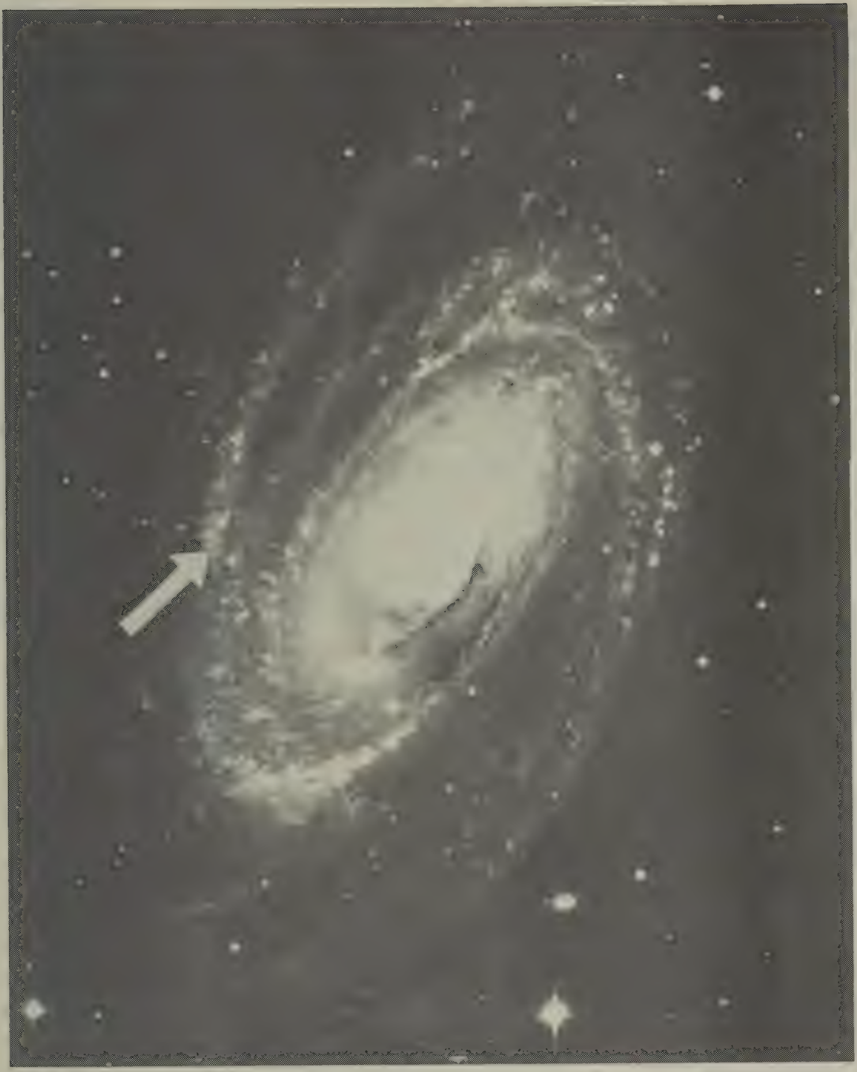
The galactic neighborhood diagram must be reduced by a factor of 7500 from the Step 6 diagram to be the proper relative size. The dots showing the galactic neighborhood and other objects are relatively much too large.

The light and radio waves we receive from the quasar OQ172 have been traveling nearly 14 billion years to reach us. This means that we observe it, not as it is today, but as it was nearly 14 billion years ago. The farther an object is from us, the farther back in time we see it.

THE EARTH FROM THE MOON

Earth-rise from the moon, the view that has turned man around. This is where we live as seen from a distance of one light second, a very close view. (Courtesy of NASA)

OUR GALAXY FROM AFAR

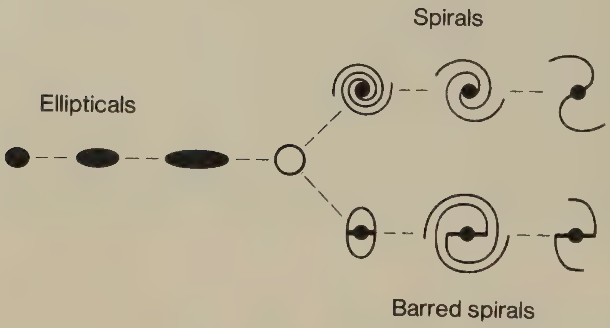


If we could travel 10 million light-years out into space and look back this is how our galaxy might appear. The arrow points to the place where we live inside a spiral arm but we couldn't see our sun from this distance. The entire solar system is so insignificant that it is smaller than the tiniest dot in the picture, and invisible among the one hundred million other stars of our galaxy which turns slowly like a great wheel in space.

This view is a photograph of a beautiful spiral galaxy which is believed to closely resemble our own. It is object number 81 in Charles Messier's list of 1784. (See page 62). (Courtesy of K. Aa. Strand).

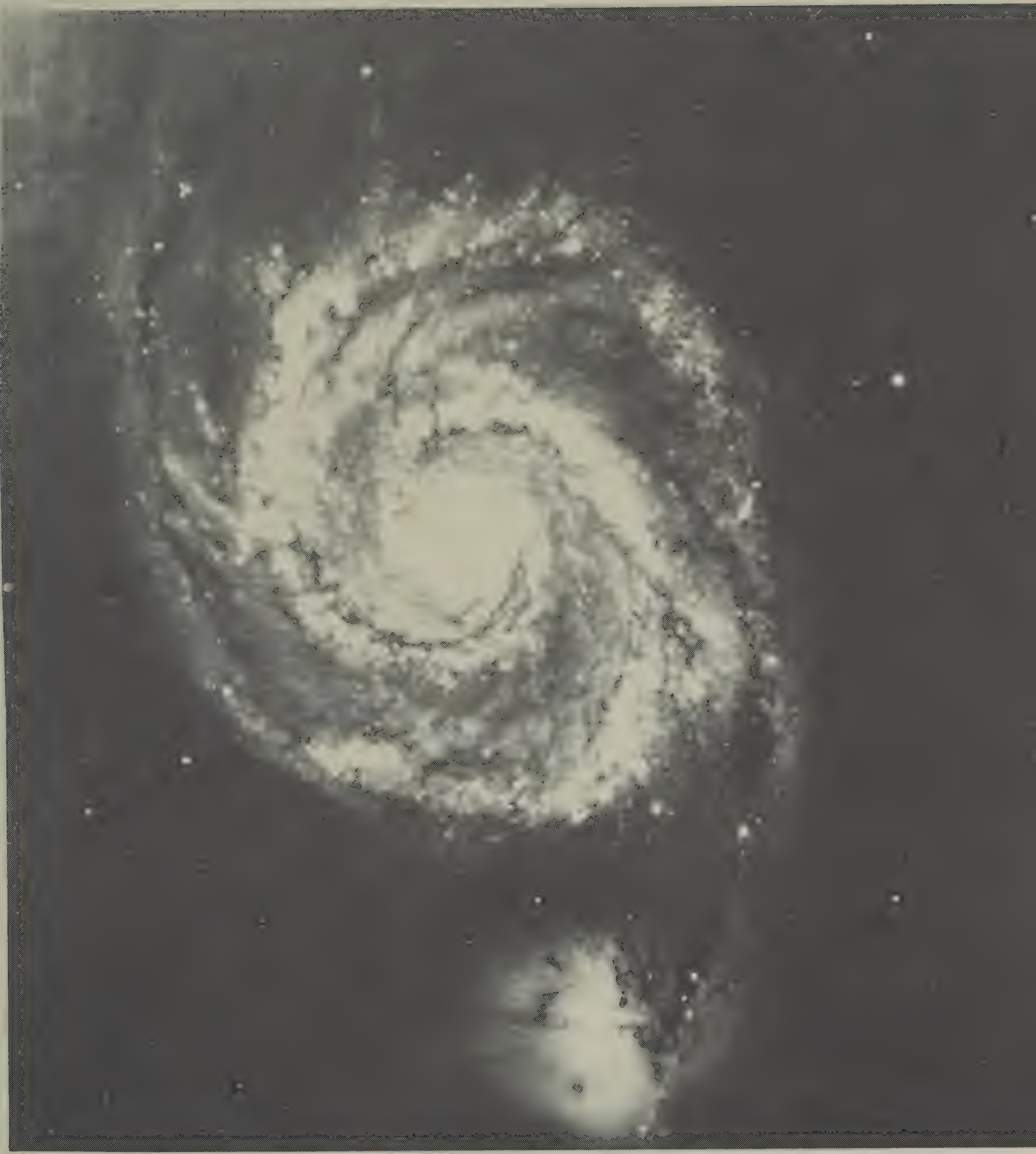
EDGE-ON GALAXY

A galaxy seen edge on from a distance of several million light-years. Compare with edge-on sketch of our galaxy (page 17). It is one of thousands of nebulas and galaxies listed in a catalog of nebulas published in 1864 by Sir John Herschel, son of William Herschel. (Courtesy of K. Aa. Strand).



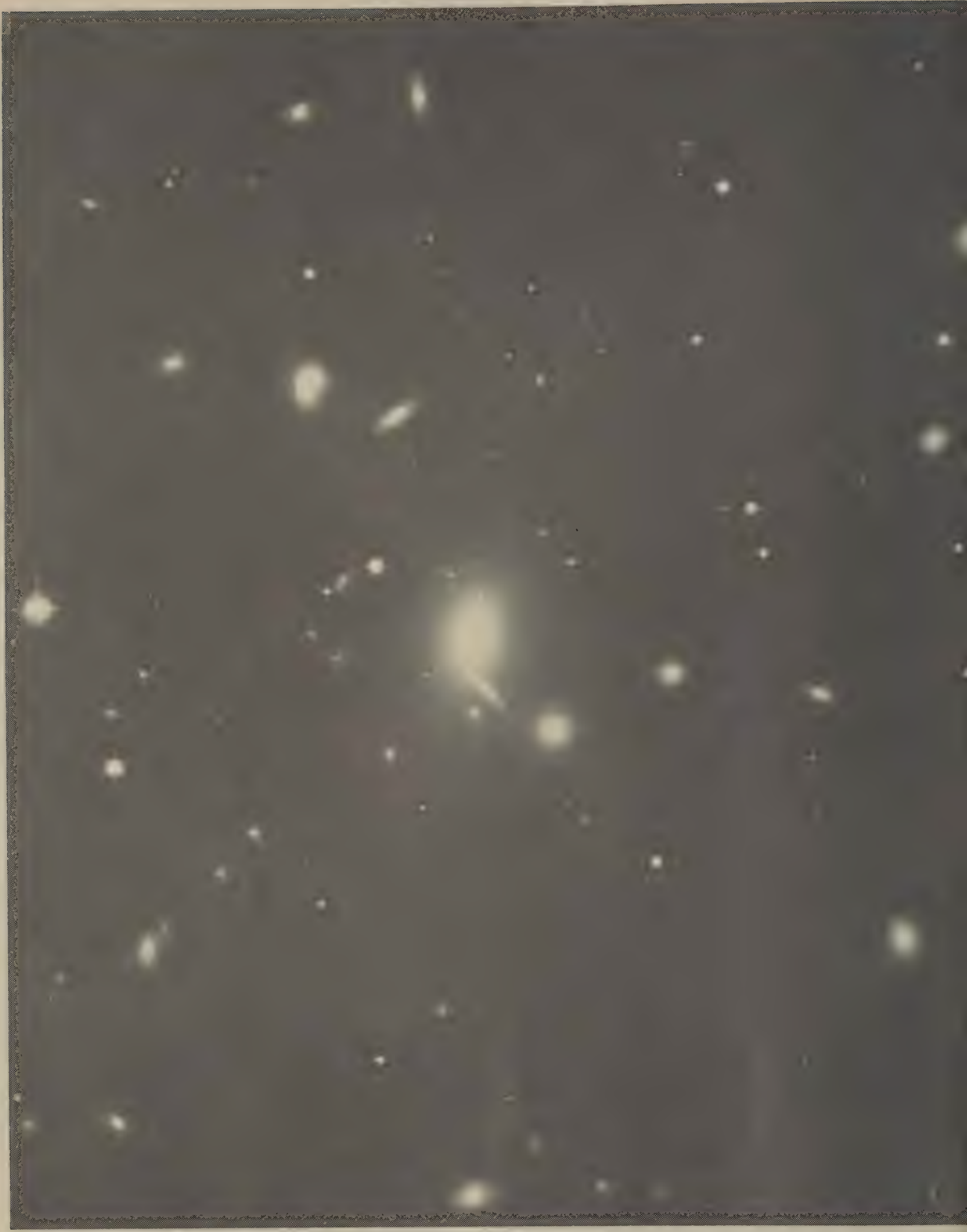
Hubble's classification of galaxies into ellipticals, spirals and barred spirals.

BROADSIDE GALAXY



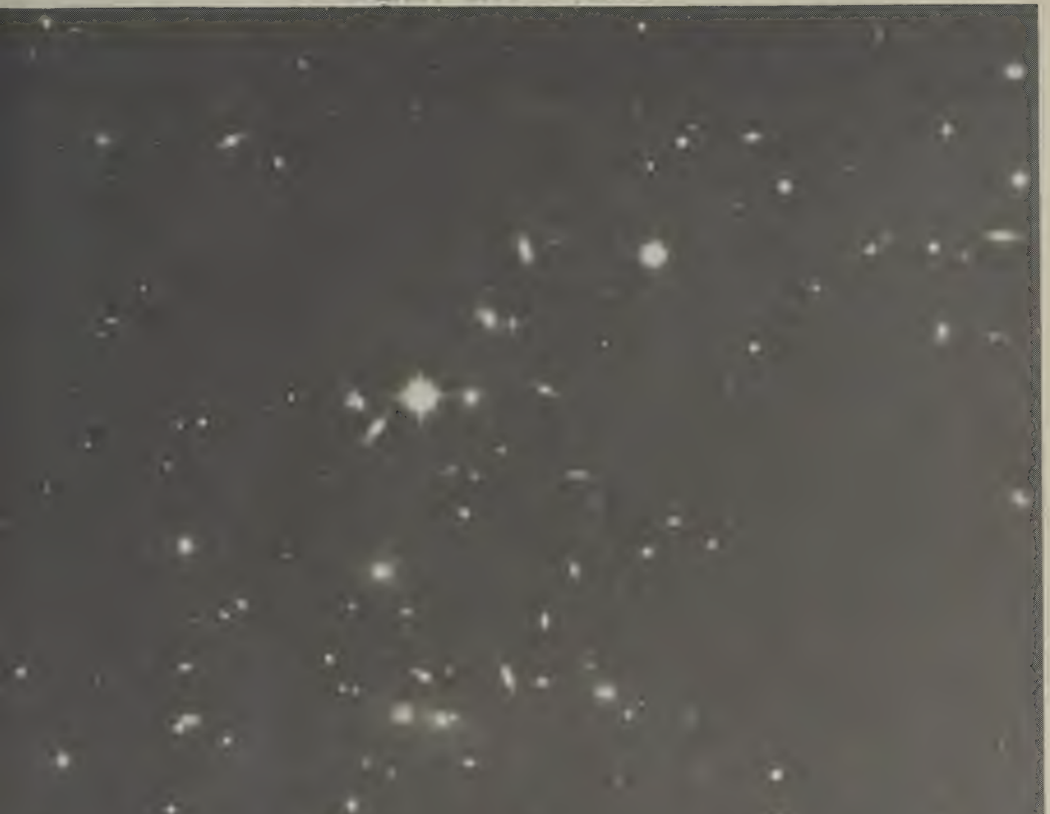
A spiral galaxy seen broadside from a distance of several million light-years. Compare with broadside sketch of our own galaxy (page 17). This is the Whirlpool galaxy near the end of the Big Dipper. It is object number 51 in Messier's list. The galaxy is a strong radio source and the bright knot at the bottom, like the tuft on a lion's tail, is a strong infra-red source. (Courtesy of Hale Observatories)

A DEEP VIEW

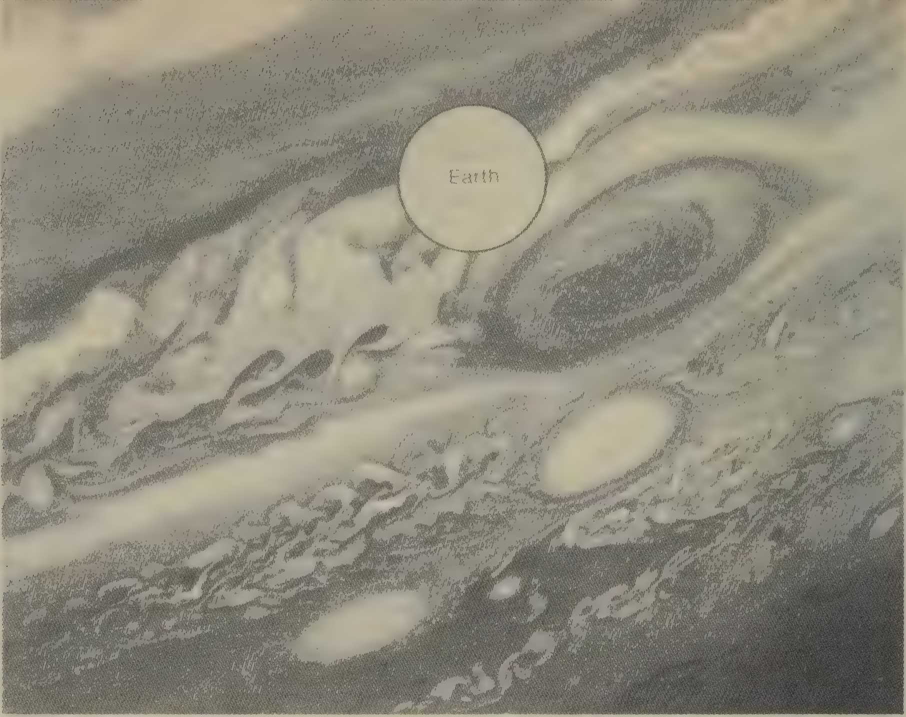


Cluster of galaxies at about 100 million light years distance in the constellation Coma Bernices as seen with the 5-meter Palomar telescope. Some galaxies are seen edge-on, others broadside (fuzzy discs) and some at other angles. Although a deep view, the distance is only about one percent of the radius of the universe. (Courtesy of Hale Observatories)

A DEEPER VIEW



Cluster of galaxies at about 250 million light years distance in the constellation Corona Borealis as seen with the 5-meter Palomar telescope. Including the faint ones there are over 100 in the photograph. The three round bright objects with perpendicular spikes are nearby stars in our own galaxy. Although this is a deeper view, the distance is only a couple of percent of the radius of the universe. Clusters of galaxies, as in this view, are often the source of radio and x-ray radiation. (Courtesy of Hale Observatories)

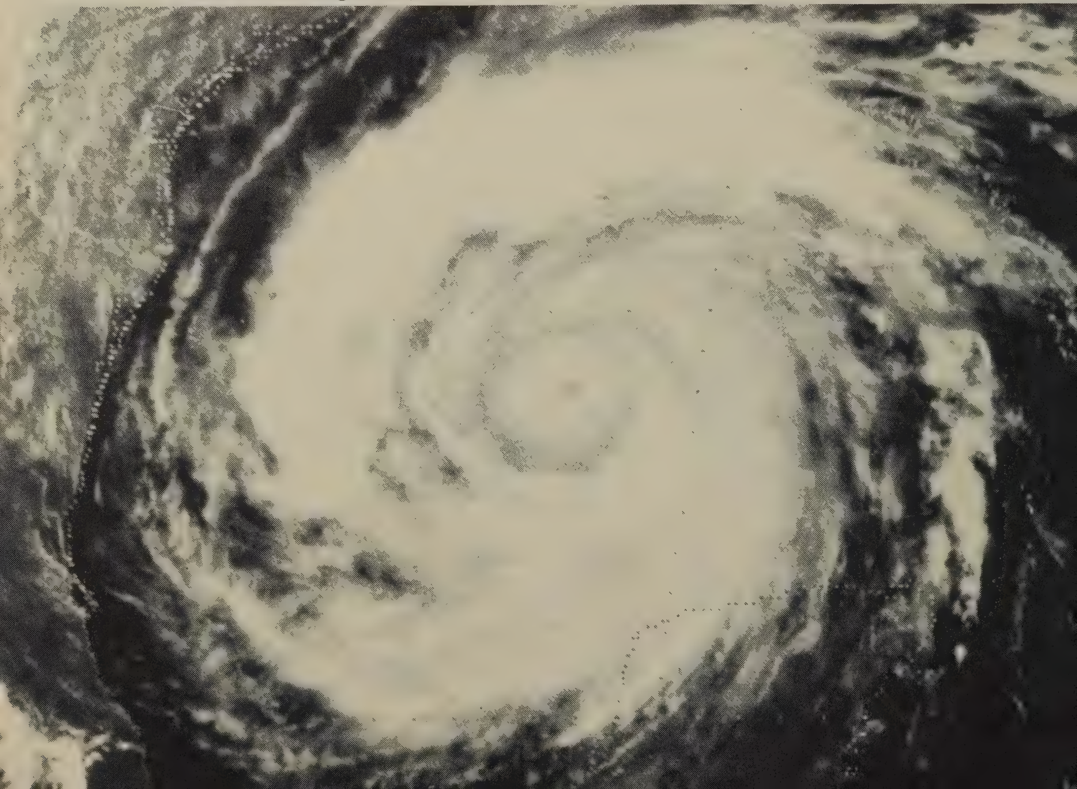


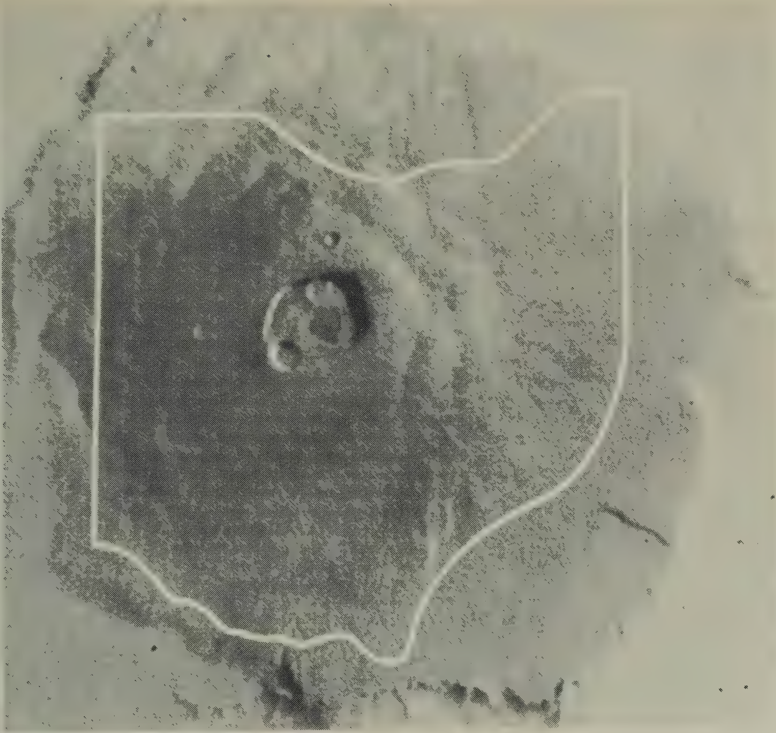
PROMINENT FEATURES

Jupiter's Great Red Spot, larger than the earth, is like a giant persistent hurricane. A big white spot is just below.

Nix Olympica, larger than Ohio, is a mammoth volcano on Mars.

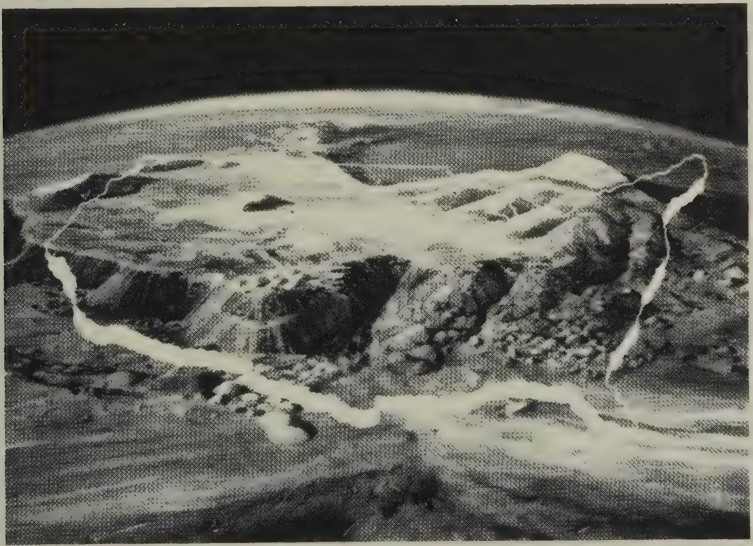
Big white spot on the earth: hurricane Allen filling the Gulf of Mexico, at noon on August 8, 1980.

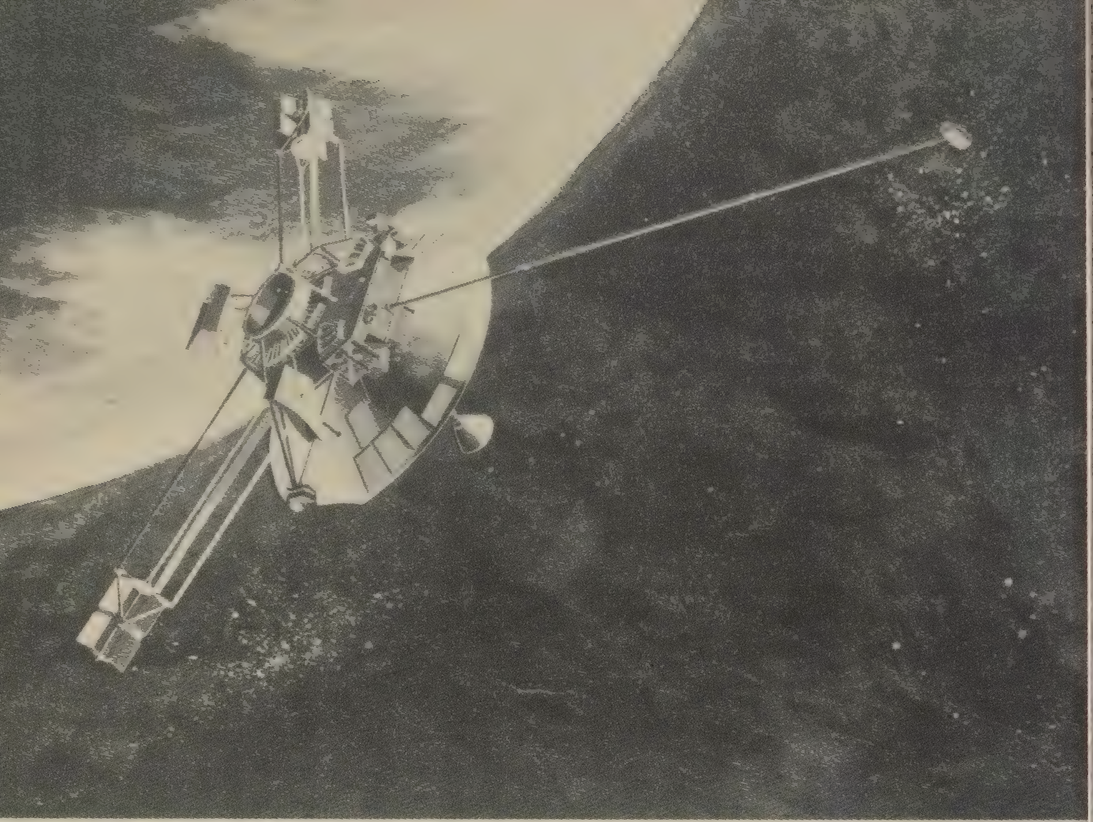




OF FOUR PLANETS

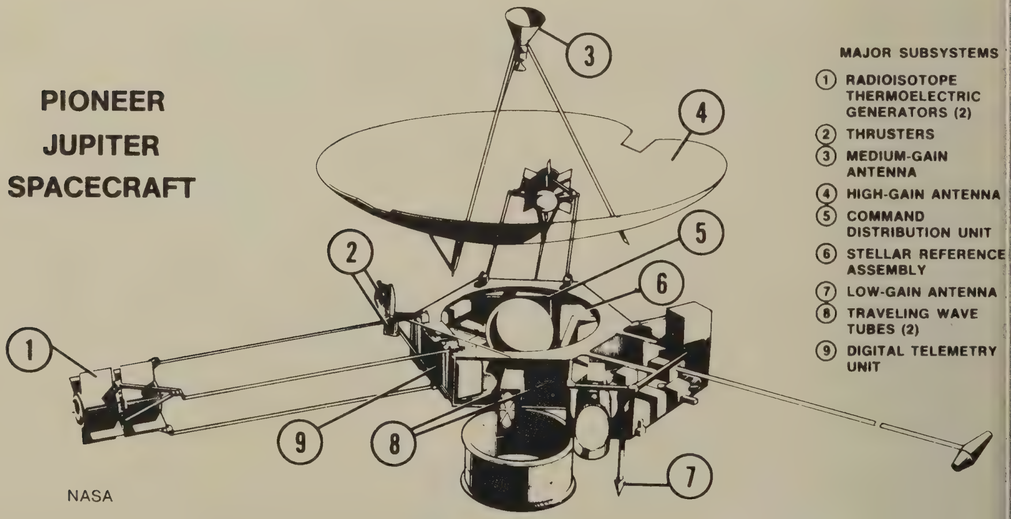
The Ishtar Terra Highland of Venus, as large as the U.S. (48 states), in a view obtained by the radar equipped Pioneer Venus spacecraft orbiting above the dense atmosphere of Venus which is opaque to light but not to radio or radar waves. (Photographs courtesy of NASA and NOAA/NESS).





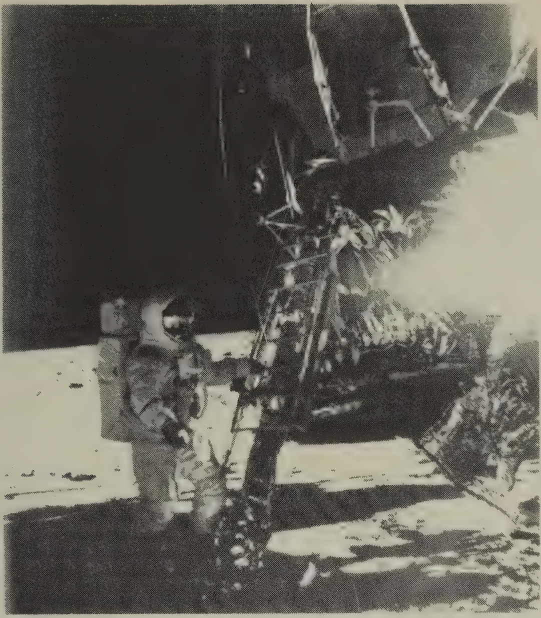
NASA

Artist's concept of Pioneer spacecraft passing Jupiter.



NASA

Details of Pioneer Jupiter spacecraft.

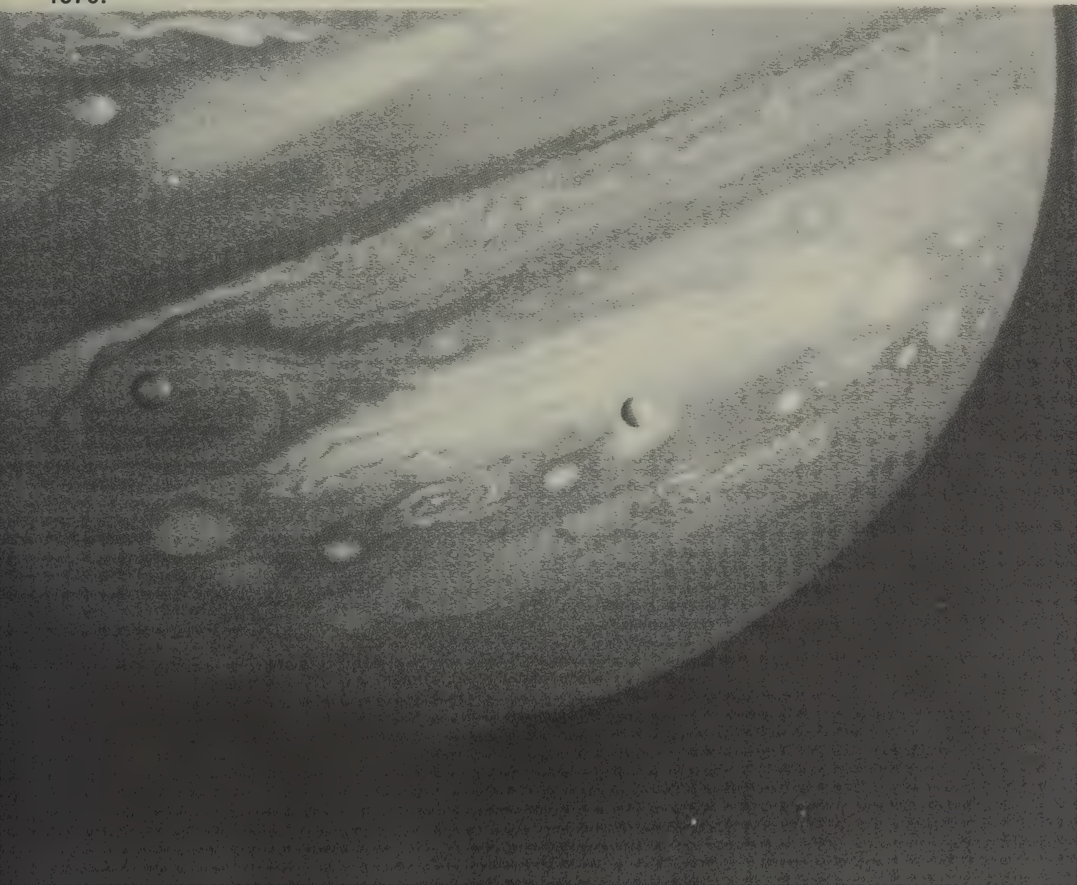


NASA

“One small step for a man, one giant leap for mankind.”

Jupiter and two of its satellites, Io at left and Europa at right, above Jupiter’s great Red Spot. Photographed by Voyager 1 on February 13, 1979.

NASA



From the Atomic to the Astronomic: A Chart for Everything in the Universe

Everything in the universe from enormous galaxies to tiny atoms has a size, which can be expressed as a maximum length or diameter and a mass. The accompanying **Mass-Size Diagram** displays objects from a helium nucleus to clusters of galaxies and the universe itself, each point on the chart indicating the mass of an object (in kilograms) and its size (in meters).

On the assumption that the object is spherical or cubical, the size dimension is indicative of its volume. The ratio of the mass to the volume of an object is a measure of its *density.* Thus, a cubic meter of air has a mass of about one kilogram but a cubic meter of lead has a mass 10,000 times as much, so relatively speaking, air is said to have a *low density* while lead has a *high density.* Water is intermediate with a density about 800 times that of air but one eleventh that of lead. From the position of an object on the chart its (average) density can be inferred. Thus, the chart also serves as a **Density Diagram** for everything in the universe. Objects on the slanting line have the density of water with densities increasing to the left of the line and decreasing to the right. Atomic nuclei and degenerate matter in the form of neutron stars and black holes have the greatest density of anything in the universe while galaxies or the universe itself have the lowest densities, being equivalent on the average to an extreme vacuum.

There is a tendency for large objects to have a lower density and small objects a higher density. The earth and living objects are in between with densities near that of water.

The figure is constructed with logarithmic scales so that the enormous ranges of mass, size and density are greatly compressed.

To summarize:

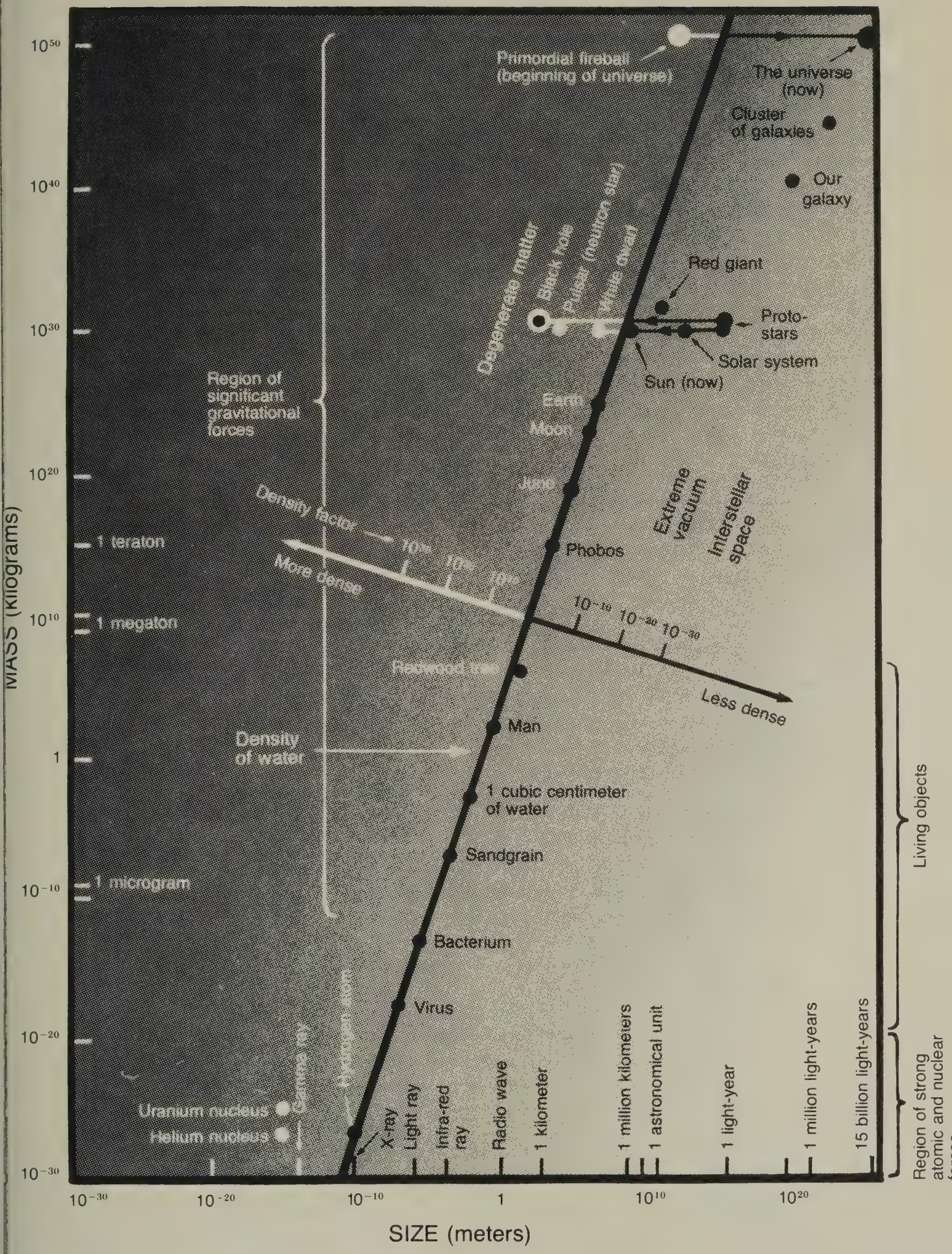
- Black holes have enormous densities.
- A pulsar (neutron star) is almost as dense, a thimble full weighing as much as 50,000 Empire State Buildings.
- Galaxies have low densities.
- The earth and living objects are in between.

A chart for everything in the universe from a tiny atomic nucleus to the largest galaxy to the universe itself.

Each point indicates the mass of an object (in kilograms) and its size (in meters). The (average) density of the object is also indicated in terms of the density of water (heavy slant line), densities being greater to the left of this line and less to the right.

Note that the universe during its evolution progressed from a high density to a low density while a gas and dust cloud (proto-star) during its evolution into a star and finally a black hole progresses from a low density to a very high density. (See page 262 for meaning of units and prefixes). (Adapted from J.D. Kraus, "Radio Astronomy," McGraw-Hill, 1966).

MASS-SIZE CHART



Waves, Rays and Particles from the Cosmos

Electromagnetic waves (photons)
  Gamma rays (shortest electromagnetic waves)
  X-rays
  Ultra-violet rays
  Light waves or rays
  Infra-red waves
  Radio waves (longest electromagnetic waves)
Gravity waves (gravitons)
Particles
  Cosmic rays
    Protons
    Nucleons, mesons
    Atomic nuclei (ions)
    Electrons
  Neutrinos

Constituents of the Universe

1. **Planets** (Earth), Satellites (Moon), Comets (Halley's)
2. **Stars:** Red giants (Betelgeuse), Blue giants (Rigel), Red dwarfs (Barnard's star), Yellow dwarfs (Sun), Main sequence stars (Sirius, Sun).
   Collapsed stars: White dwarfs (Companion to Sirius), Neutron stars or pulsars (Crab), Black holes (Cygnus-X1?).
   Exploded stars: Planetary nebulas (NGC 7293), Supernovas (Crab, Cas A).
   Double stars (Sirius and companion)
   Star clusters (M5)
3. **Galaxies:** Spiral (Our own, M31), Elliptical (M87), Irregular (Magellanic clouds).
   Clusters of galaxies (Coma)
   Radio galaxies (Cygnus A)
4. **Quasars** (OQ172, 3C273)
5. **Gas** (Hydrogen) and **dust** (Silicon compounds(?), carbon particles(?)).
6. **Molecules** in space (Ammonia, water, ethyl alcohol)
7. **Cosmic rays** (Electrons, protons and heavier atomic nuclei) and **Neutrinos** .
8. **Radiant energy** (Electromagnetic waves, gravity waves).
9. **Life** (Known only on the earth).

Waves of all Kinds

There are water waves, sound waves, heat waves and many more kinds of waves. Although they may differ in certain respects, they all have one thing in common: They move or travel with a characteristic velocity. Sound waves travel in air 1000 feet per second while radio waves can travel the earth's diameter in 1/20 of a second.

We can divide waves in general into two groups: (1) those that travel only through solids, liquids and gases, and (2) those that can travel through vacuum (or empty space).

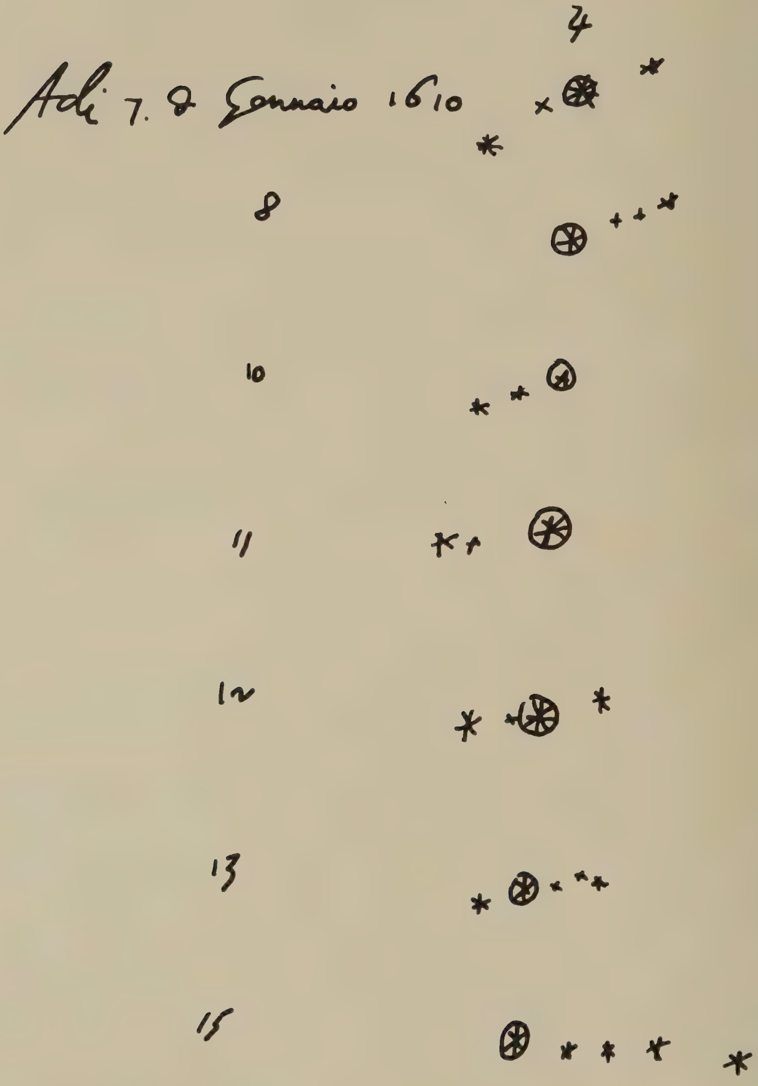
The first group we might describe as **mechanical waves**, including:
Water waves, visible on the surface of lakes or oceans,
Seismic waves, or vibrations transmitted through the ground from earthquakes, **Sound waves**, by which we hear,
Waves on strings or wires, as in musical instruments.

The second group embraces the **electromagnetic waves**, including:
Radio waves, which carry AM, FM, TV, radar and all kinds of communications.
Infra-red waves, or heat waves, which warm our bodies,
Light waves, by which we see,
Ultra-violet waves, which can sterilize and tan,
X-rays or waves, which doctors and dentists use to see through our bodies,
Gamma-rays or waves, which are emitted by some uranium products and in vast amounts by nuclear explosions.

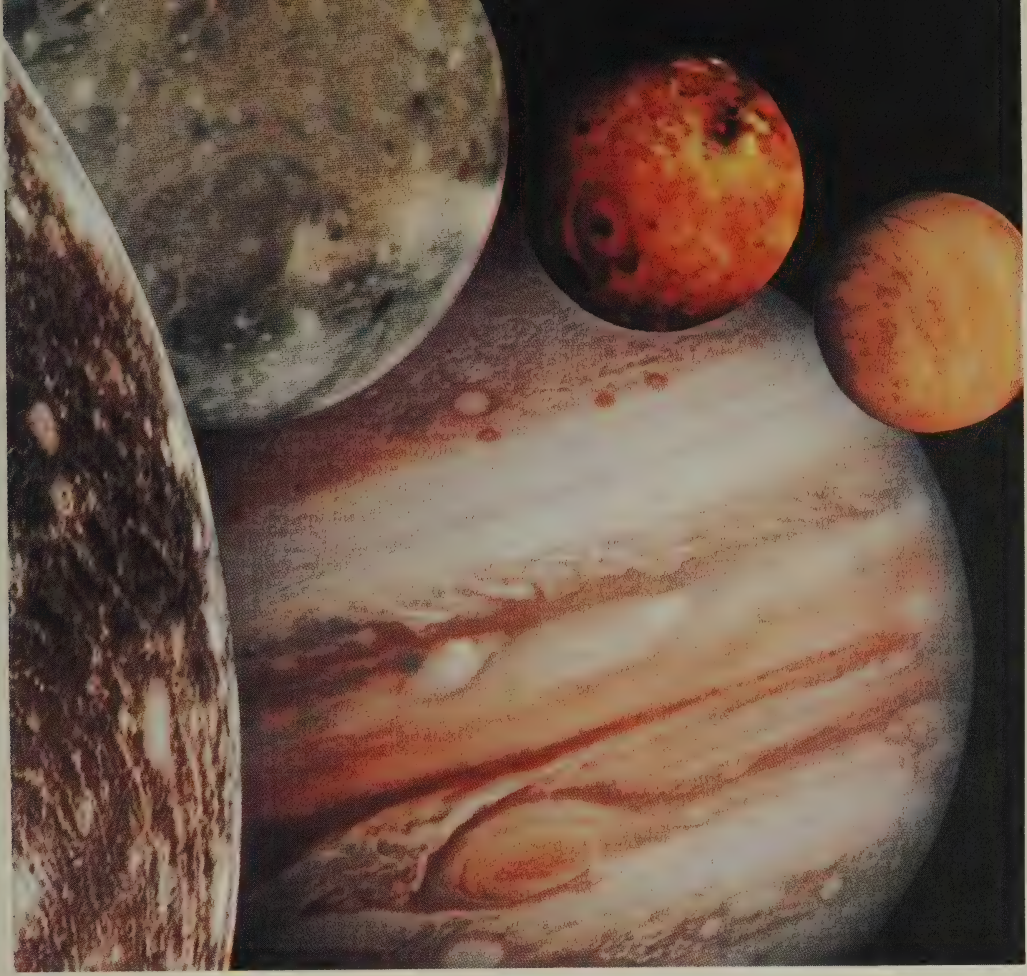
All of these waves are fundamentally similar, involving the propagation of electric and magnetic effects at a speed in air or vacuum, of 300,000 kilometers per second. They differ in wavelength from the radio waves at the long wavelength end to gamma waves at the short wavelength end. The range in wavelength is enormous. Radio waves may be many kilometers in length while gamma rays, on the other hand, are so short that it takes a billion of them to stretch across the dot or period at the end of this sentence. The relationship of these waves is presented by **The Electromagnetic Spectrum**, with scales of wavelength in metric units.

What we have called electromagnetic *waves* are also rays and what we have called electromagnetic *rays* could equally well be described as waves. The term *wave* calls attention to the wave nature while the word *ray* emphasizes the path of propagation which is a straight line in a uniform medium.

The wavelength (in meters) equals the velocity (in meters per second) divided by the frequency (in hertz) OR the frequency equals the velocity divided by the wavelength. Thus, for electromagnetic waves (velocity 300 million meters per second), a wavelength of 300 meters corresponds to a fre-



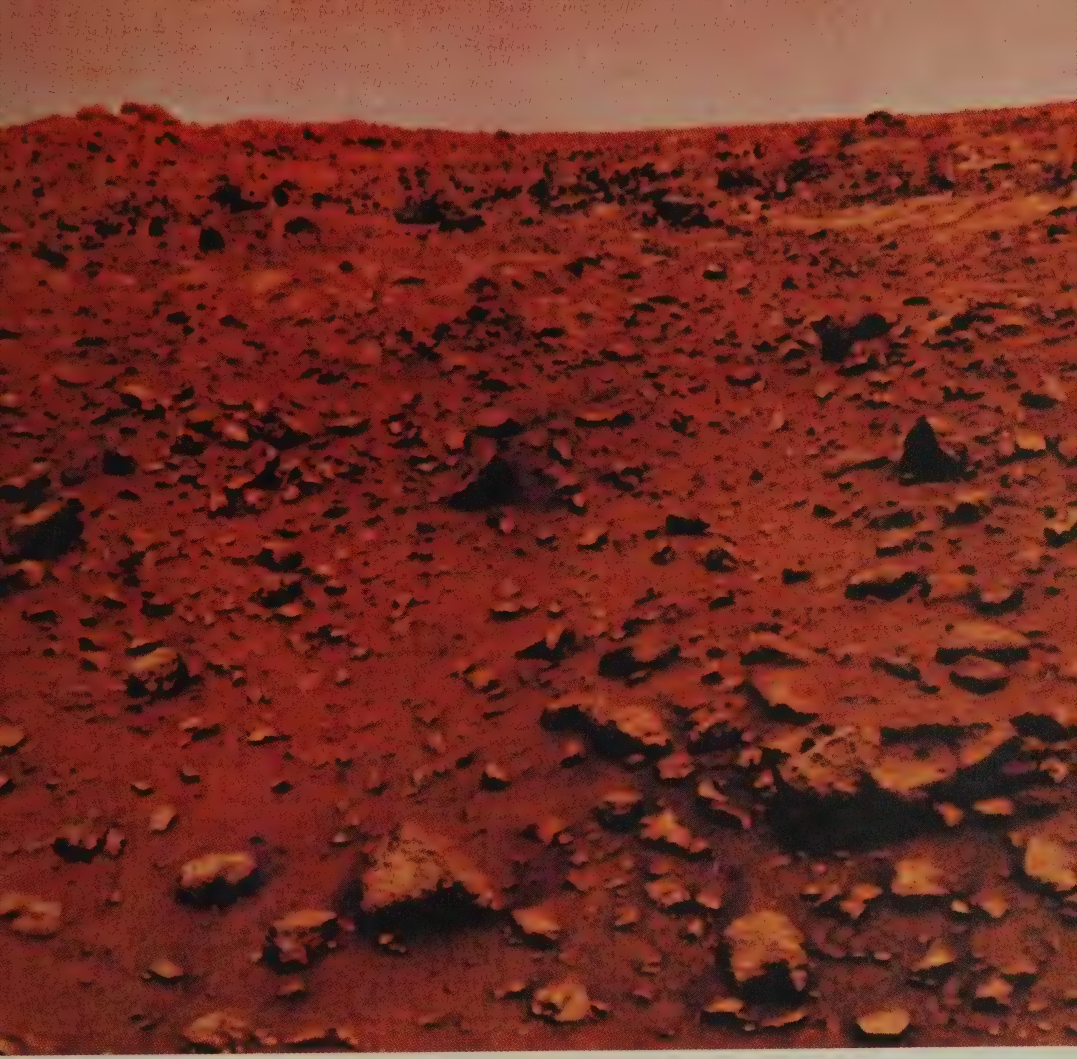
What Galileo saw, as entered by him in his notebook. On the 7th of January, 1610, he saw Jupiter with two star-like moons to the east (left) and one to the west. The next night there were three to the west. The 9th was cloudy but on the 10th and 11th he saw two to the east. On the 12th there were two to the east and one to the west. On the 13th there were three to the west and one to the east. The 14th was cloudy and on the 15th he saw four moons all to the west.



What Voyager saw. For nearly 4 centuries after Galileo little was known about Jupiter's moons. But in 1979 Voyager brought us close-up pictures in rich detail showing a surprising contrast in their appearance. Left to right the moons are Callisto, Ganymede, Io and Europa with Jupiter in the background.

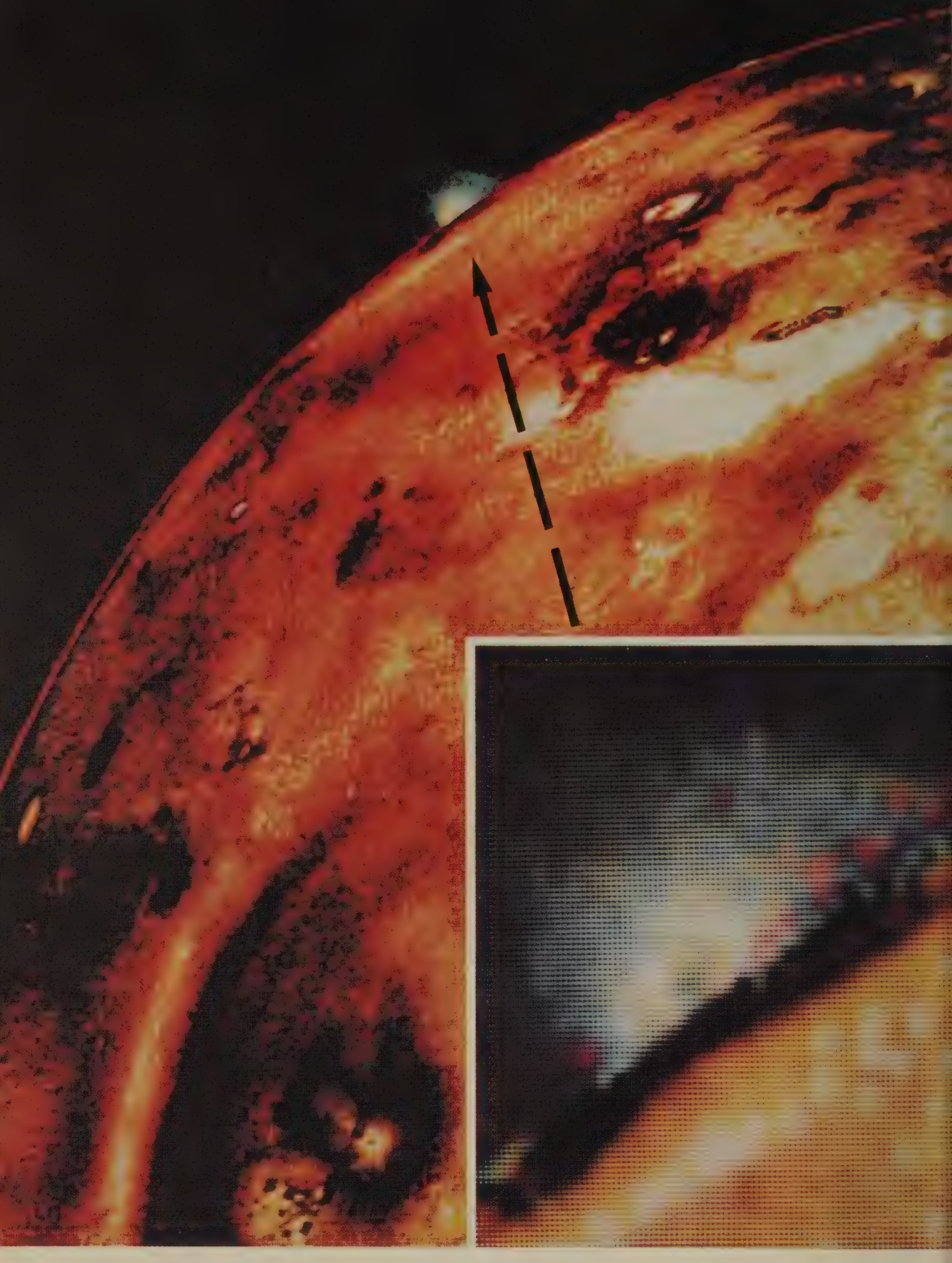
The moon Io, slightly larger than the earth's moon, has a relatively smooth surface mottled bright orange-red and a number of active volcanos around its equator, some spewing plumes of gas. Jupiter's ring may be formed of some of this volcanic material which has escaped into space.

The moon Europa has long linear marks criss-crossing its surface which are probably cracks in an icy surface. Ganymede, the largest of Jupiter's moons, looks more like the earth's moon with many crater marks evident but with no major elevations. Its surface may be a mixture of ice and rock. Callisto, the most remote of the four Galilean moons from Jupiter, has an enormous multi-ring meteorite impact basin with a light-colored central circular patch hundreds of kilometers across with ridges extending out more than 1000 kilometers. (Courtesy of NASA and the Jet Propulsion Laboratory).



Close-up of the surface of Mars showing rocks, soil drifts and other features near the Viking I lander. This picture of Mars was taken July 21, 1976, the day following Viking 1's successful landing on the planet. The local time on Mars is approximately noon. The view is southeast from the Viking. Orange-red surface materials cover most of the surface, apparently forming a thin veneer over darker bedrock exposed in patches, as in the lower right. The reddish surface materials may be limonite (hydrated ferric oxide). Such weathering products form on the earth in the presence of water and an oxidizing atmosphere. The sky has a reddish cast, probably due to scattering and reflection from reddish sediment in the lower atmosphere. (Courtesy of NASA)

Facing page. Top. Solar corona from Skylab. Colors indicate levels of brightness. Center. Earthrise from the moon with Jupiter, Venus, Mercury, Mars and Saturn in a mosaic. Bottom. Montage of the four inner planets, Mars, Earth, Venus and Mercury. (Courtesy of NASA).



NASA

Surface of Jupiter's moon Io with volcanic eruption in progress. The eruption is shown in more detail by the inset at the lower right. Photographs by Voyager 1 on March 4, 1979.

quency of one million hertz. As another example, a wavelength of 21 centimeters (0.21 meters) corresponds to a frequency of 1420 million hertz. And as an example involving light, rays of a greenish hue (500 nanometer wavelength) correspond to a frequency of 600 billion billion hertz.

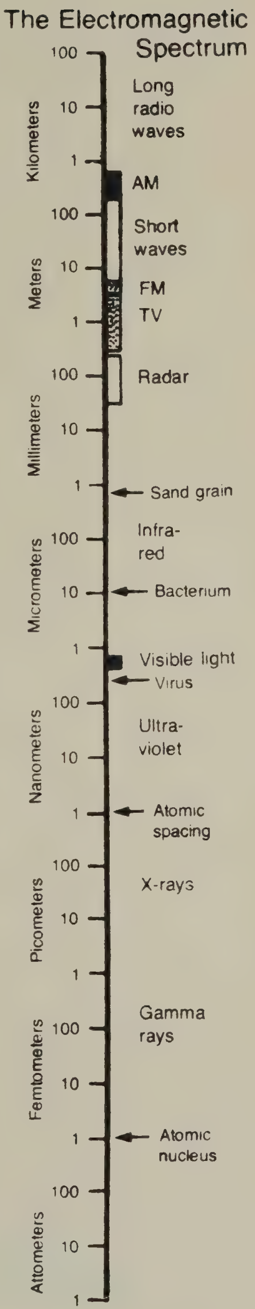
All electromagnetic waves (or rays) are conveyed in "packets" of energy or "wave trains" called *photons*, the energy of the photon being proportional to the frequency. Thus, the higher the frequency (or the shorter the wavelength), the greater the photon energy. The photon energy can be used to describe a wave and for x-rays and gamma rays this is customary, with the photon energy being expressed in electron volts.

Thus far we have neglected mention of another kind of wave which is believed to travel through empty space at the same speed as electromagnetic waves, yet it isn't an electromagnetic wave. This is the **gravity wave** discussed in more detail later on. By analogy with the photon of electromagnetic waves, gravity waves are believed to be conveyed in energy packets called *gravitons*.

Gravity waves are presumably radiated by rotating double star systems and during catastrophic events such as a stellar collapse into a pulsar or black hole. If the rotating star system made one revolution per week the wavelength would be gigantic: one-half light week. The distance to the moon is only one light-second so the gravity wavelength from the stars would be seven times the diameter of our solar system. Some day we may be able to detect such waves.

To summarize:

- A sound wave can travel through air but not through vacuum.
- Radio waves and light waves are electromagnetic waves.
- Gravity waves are believed to travel as fast as electromagnetic waves but are not electromagnetic.


The Electromagnetic Spectrum

The electromagnetic spectrum or wavelength scale from the shortest gamma rays to the longest radio waves. The wavelengths for AM, FM and TV broadcasting, for radar and for visible light are indicated. The size of objects including a sandgrain, a bacterium, a virus, the spacing of atoms and an atomic nucleus are shown for comparison. (See page 262 for meaning of prefixes).

Telescopes for Exploring the Cosmos

The mystery of the heavens has stirred man's curiosity and imagination since the beginning of time. Ancient civilizations have left behind a rich treasury of lore and legends about the sun, the moon, the stars and the planets.

The first calendars were devised from the motions of celestial bodies. Navigators used the stars to guide them. But the sky the ancients thought of as a shell on which the stars moved, we realize is a window on the vast cosmos which is our total environment.

From observations with telescopes of all kinds, man's eyes on the universe, has come a better understanding of this all-encompassing environment, a universe of boundless energy and enormous contrasts. We also have come to appreciate something of the small size and finiteness of our earth and its relative insignificance compared to our galaxy and the great universe beyond. Astronomical observations draw man out of his self-centered world and can give him a cosmic perspective.

The more we learn about other stars the better we understand our sun and its thermonuclear processes which provide the light and heat necessary to sustain life on the earth. The more we learn about our own and other galaxies, their evolution and destiny, the better we understand how the earth evolved and what its fate may be.

The faint and fragile waves from distant space are the message carriers which tell man all he knows about the depths of the cosmos. The main function of a telescope is to collect these waves over as large an area as possible and bring them to a focus where they can be detected by a receptor such as the eye, photocell, photographic plate, radio receiver or other device.

The telescopes used for observing the sky over the electromagnetic spectrum may differ markedly in appearance but there are several basic principles in common:

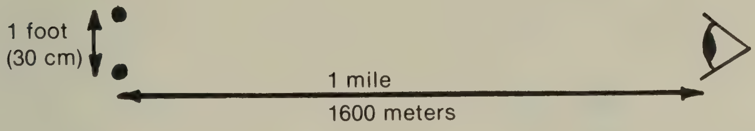
(1) All are *energy collecting devices.* The larger the collecting area, or aperture, the greater the energy collected and the greater the sensitivity.

(2) All can separate or resolve two adjacent objects such as stars in proportion to the aperture diameter or dimension. The greater a telescope's aperture the larger its *resolving power* or *resolution*, that is, its ability to separate closely-spaced objects.

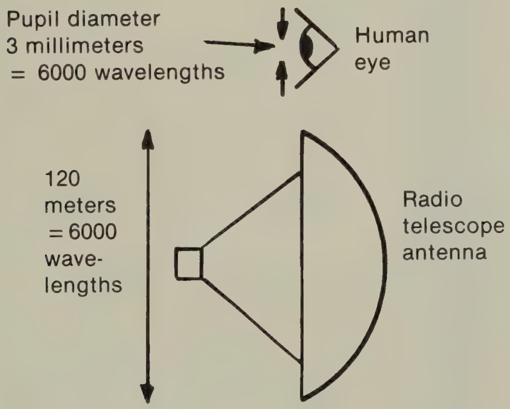
An approximate but useful formula is that the resolution angle is equal to 60 degrees divided by the diameter of the telescope in wavelengths.

The human eye has a nominal pupil diameter of about 3 millimeters. This is its aperture diameter. At a nominal light wavelength (green light of 500 nanometers) the eye diameter is equal to 3 millimeters divided by 500 nanometers or 6000 wavelengths. Thus, the resolution for the eye is 60° divided by 6000 or 0.01°, which means that the eye can just distinguish between two objects separated by one-hundredth of a degree. This is the angle between two objects a foot apart as seen from a distance of one mile. If the objects are closer together, the eye cannot separate them; they blend or blur together to form a single object.

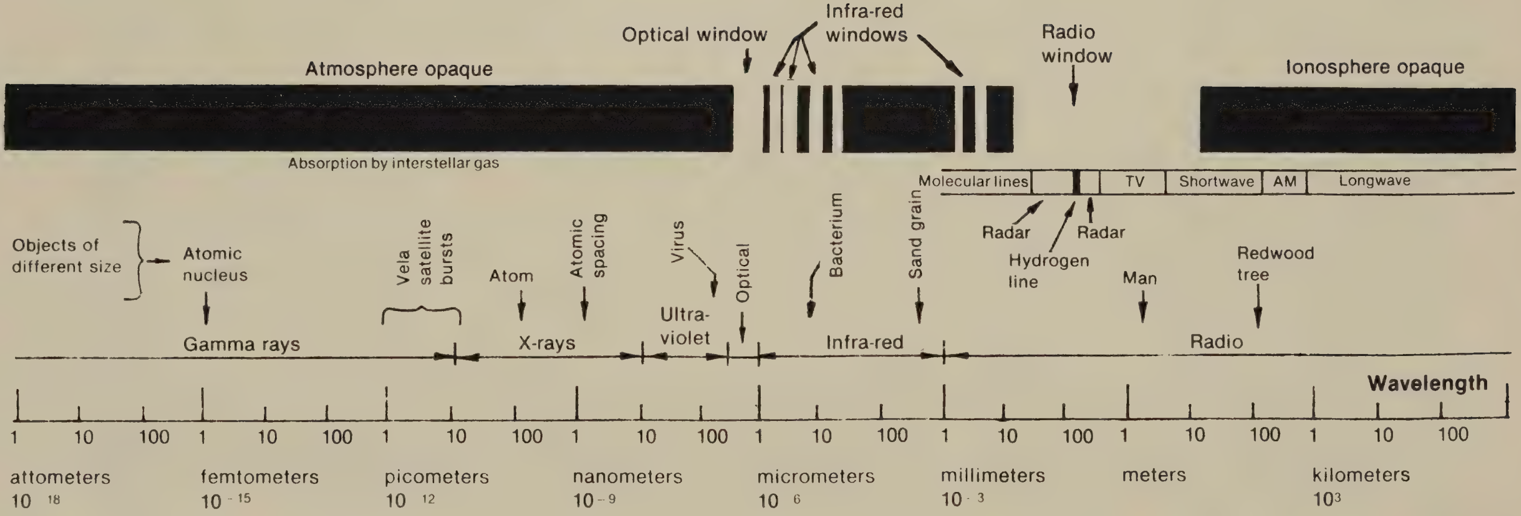
Galileo's telescope had a diameter of 56 millimeters (19 times the eye's pupil diameter) so he could resolve or distinguish between objects separated by only one-nineteenth of 0.01°.



A radio telescope 120 meters in diameter operating at a wavelength of 2 centimeters has a diameter of 6000 wavelengths (120 meters divided by 2 centimeters). Thus, its resolution is 60° divided by 6000 or 0.01°, the same as for the human eye. Although the huge radio telescope has no better resolution than the eye, its collecting area or aperture is over a billion times greater making it a very sensitive device.



A radio telescope 120 meters in diameter operating at a wavelength of 2 centimeters has the same resolution as the human eye.



The electromagnetic spectrum with wavelength on a logarithmic scale from the shortest gamma rays to the longest radio waves. Wavelengths are expressed in metric units. The atmospheric opacity is shown at the top with the optical and radio windows in evidence.

Referring to the **Electromagnetic Spectrum Diagram** the dark band along the top is indicative of the opacity or transparency of the earth's atmosphere (and ionosphere). Over most of the electromagnetic spectrum the atmosphere is opaque. The two principle exceptions are a narrow band of optical wavelengths somewhat shorter than 1 micrometer and a much wider band of radio wavelengths between roughly 1 millimeter and 10 meters. These transparent optical and radio regions are sometimes called the *optical and radio "windows"* of the atmosphere and ionosphere and it is through these windows that celestial observations are made from the ground.

Some infra-red and ultra-violet observations close to these windows can also be conducted from the ground but over the rest of the electromagnetic spectrum observations of the sky must be made from above most or all of the atmosphere and ionosphere.

In general, astronomical observations can be divided into those that are *ground based* and those that are not. The later group includes a wide variety: from high flying balloons and aircraft, from rockets, artificial satellites, space probes and space laboratories.

While ground-based observations are limited to the optical and radio regions and to some extent the infra-red and ultra-violet, observations from space can cover the entire electromagnetic spectrum because there is no absorption by the atmosphere. Even at optical wavelengths the conditions for observing are better in space than on the ground because variations in the bending of light by the atmosphere cause star images, as seen from the ground, to bounce or dance as though the stars are viewed through a quivering mass of jelly. In space the images are steady points. And at long radio wavelengths (longer than 10 meters) the ionosphere is usually quite opaque making a space telescope a necessity. One region of the spectrum where space telescopes have no significant advantage over ones on the ground is in the centimeter to meter radio wavelength region where stability, accessibility and lower cost give ground-based instruments a distinct advantage.

Thus far the observational techniques described are passive, depending on natural emissions from the celestial objects. In contrast to these methods, *active* techniques have been developed using laser and radar devices. Here the radiations are man made. Echoes of signals from powerful terrestrial radio transmitters have been bounced off the moon, sun and several planets. Laser-generated light and infra-red rays are also used in the same way. The length of the echo delay-time gives a measure of the distance to the object while further processing of the echoes may yield information sufficient to make maps of the objects studied. The time required to wait for the echo and the fact that the echo power decreases as the fourth power of the distance impose limitations on the practical range of these active techniques.

Besides emitting electromagnetic waves, celestial objects may radiate gravity waves or emit particles. Thus, a massive rotating double-star system sends out gravity waves which, it is presumed, travel with the speed of light. Telescopes for detecting these waves are under development.

Another technique of space exploration relies on observations of atomic particles streaming past the earth in great numbers from all directions. They include elementary particles, electrons and protons and heavier, more complex atomic particles. Collectively these particles are frequently referred to as *cosmic rays.* Being charged particles, they are deflected by interstellar magnetic fields and by the earth's magnetic field so their direction of origin may be difficult to determine. Some originate from objects such as the Crab nebula which is also a strong radio and x-ray source.

Yet another particle with potential for studies of our universe is the neutrino. Having no charge, this particle is not deflected by magnetic fields so it can travel directly from its point of origin. But the detection of such a neutral, virtually massless particle is a formidable problem.

With the development of artificial satellites and space probes the way has been opened for a more direct approach to many phases of extra-terrestrial exploration. Probes can transport sensing devices and even small laboratories for close-up observations and experiments at distant locations and telemeter their findings back to earth. The 1976 Viking landers on Mars exemplify this technique. These landers produced pictures and other information which made an earth-bound scientist feel that he was practically a visitor to the red planet. But a human's capacity for observation and interpretation of diverse and unexpected phenomena makes manned expeditions, such as the Apollo mission to the moon, the ultimate in space exploration. Probes and manned exploration may be regarded as *direct techniques* as distinguished from observations-at-a-distance using electromagnetic waves, gravity waves or atomic particles.

The difficulties and high cost of exploration by probes and man tend to limit the range of these expeditions. Ultimately the solar system may be spanned but the enormously greater distances to the nearest stars puts the use of direct techniques further into the distant future. As in the past, the indirect at-a-distance techniques will continue to be the only ones available to man for studying and exploring the more remote parts of the cosmos.

Whereas optical, radio and x-ray telescopes have detected objects at distances requiring nearly 14 billion years of light, radio or x-ray travel time, man has covered a distance of only about 1 second of wave travel time (to the moon) and probes have functioned only to distances of 1 hour or so of wave travel time (to Saturn).

In later chapters many of the above mentioned techniques will be described in more detail.

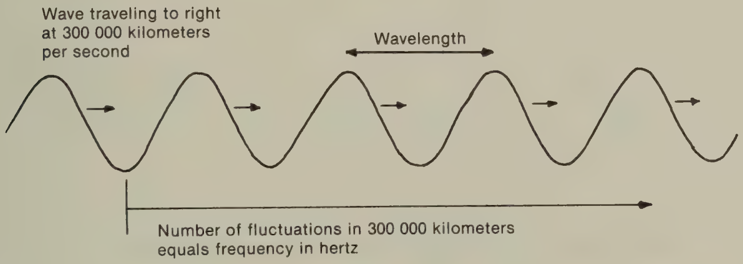
COSMIC DISTANCE TABLE

Distances in light travel time (approx.)

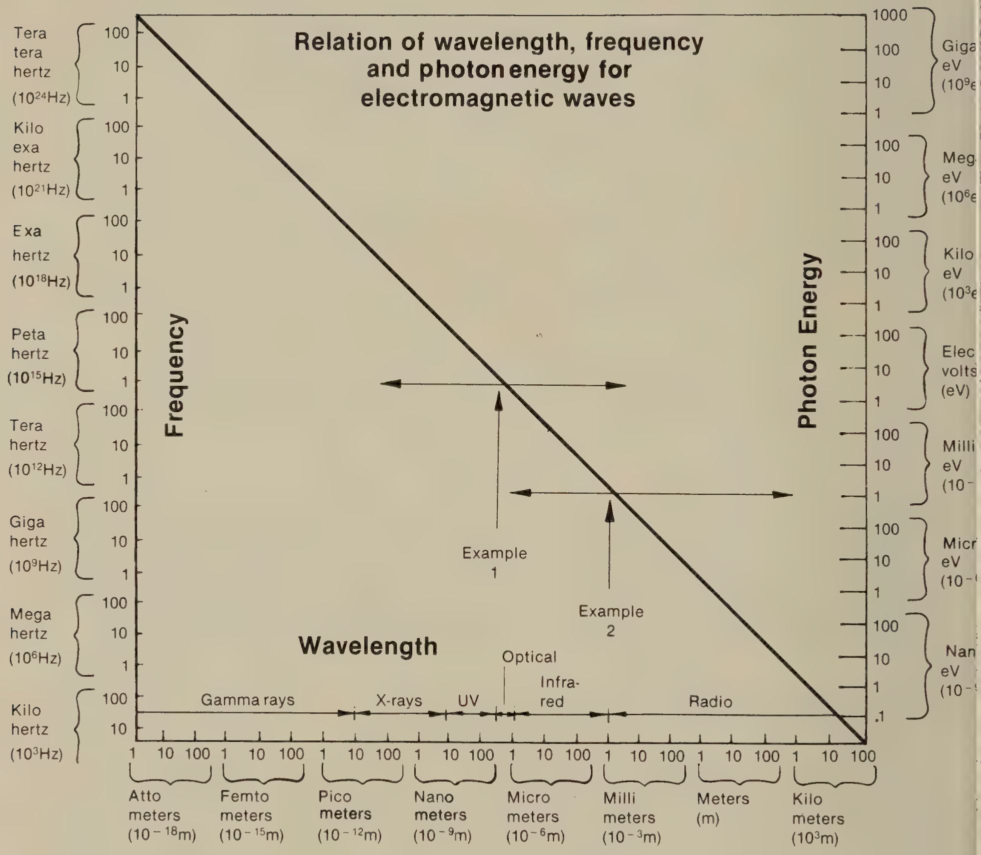
Earth to moon	1 second
Earth to sun	500 seconds (8 min.)
Sun to Mars	12.5 minutes
Sun to Jupiter	40 minutes
Sun to Pluto	5.5 hours
Solar system diameter (at orbit of Pluto)	11 hours
Sun to nearest star	4 years
Sun to center of galaxy	30,000 years
Diameter of galaxy	100,000 years
Distance of Andromeda galaxy	2 million years
Distance to "edge" of universe	15 billion years

To convert light travel time to kilometers multiply travel time in seconds by velocity of light (300,000 kilometers per second).

But while we explore the vast reaches of space we should not forget that studies of the matter of which the earth is made can tell us much about the history and nature of the universe. The earth is our most accessible astronomical object. To study it we need a shovel instead of a telescope.


Wave traveling to right at 300 000 kilometers per second
Wavelength
Number of fluctuations in 300 000 kilometers equals frequency in hertz

Schematic diagram of an electromagnetic wave traveling to the right at 300 000 kilometers per second. As the waves pass they produce an electromagnetic fluctuation at a rate equal to the number of waves passing per second. This rate is called the *frequency*. The spacing between the waves is called the *wavelength*.



Frequency, Wavelength, Photon Energy Diagram.

Example 1: A wavelength of 300 nanometers corresponds to a frequency of 1 petahertz and a photon energy of about 3 electron-volts.

Example 2: A wavelength of 1 millimeter corresponds to a frequency of 300 gigahertz and a photon energy of about 1 milli-electron-volt.

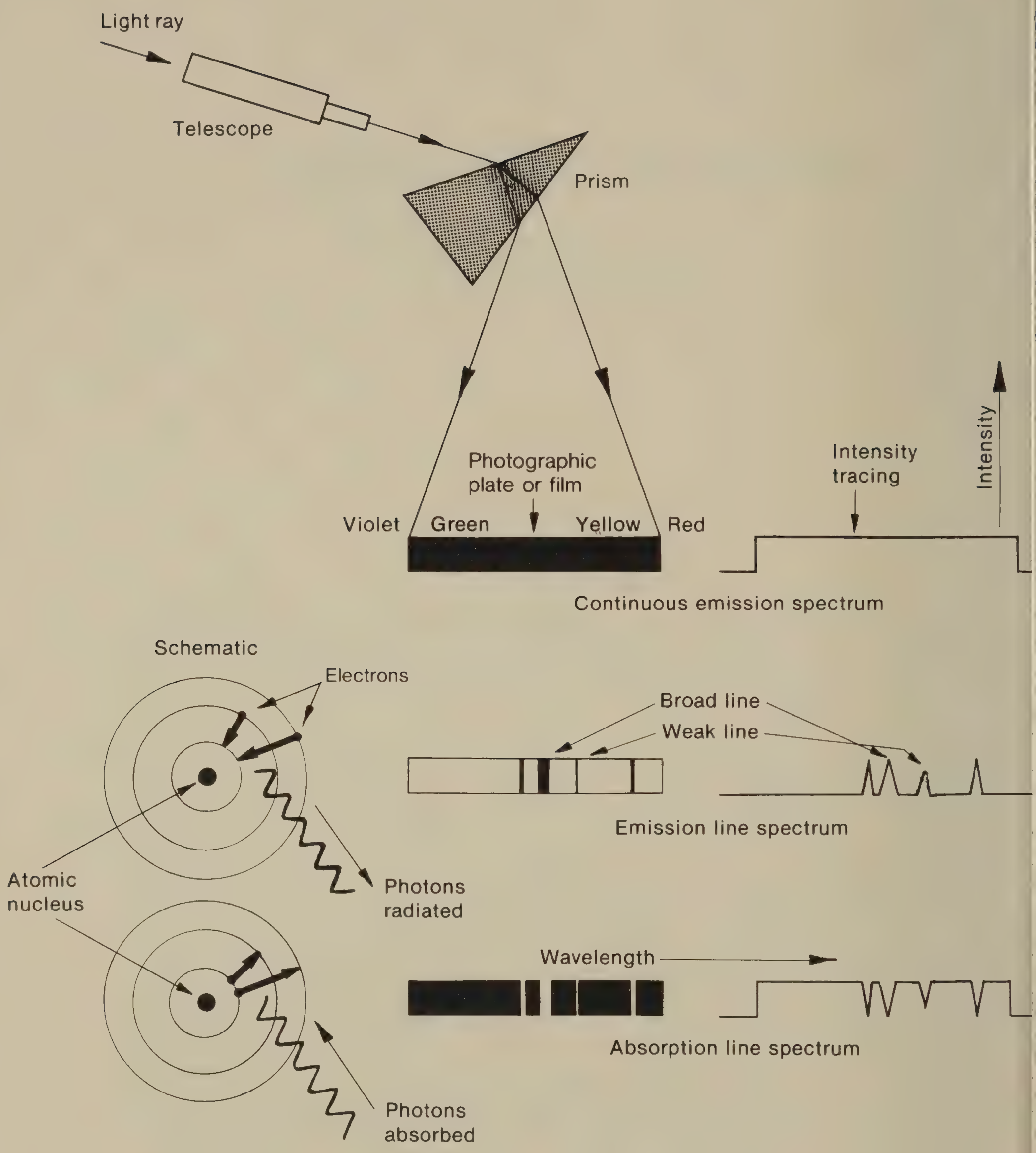
OPTICAL ASTRONOMY

Optical Spectra

When a light ray enters a piece of glass it is bent, or *refracted.* Red light is bent less than violet light so that with a prism of glass the light is spread out into its component wavelengths or colors and a *spectrum* or rainbow of colors is produced.

Spectra, both at optical and at other wavelengths, may be characterized as *continuous spectra,* in which the radiation is spread continuously over a range of wavelengths, *line spectra* in which the radiation is at specific wavelengths (called lines), or a combination of the two. Continuous spectra may be produced by emission from atoms of solids, liquids or dense gases and by free electrons. Line spectra are normally produced by emission from the atoms and molecules of gaseous media as explained below. If continuous-spectrum radiation passes through a gaseous medium having a line spectrum, absorption may occur at the line wavelengths resulting in an *absorption line spectrum* which is the reverse of an *emission line spectrum.* Continuous radiation from the sun passing through the solar atmosphere is absorbed at many wavelengths by atomic gases producing an absorption line spectrum, an effect first observed by Joseph von Fraunhofer about 1814.

An *atom* consists of a *nucleus* with one or more *electrons* circulating around it. These electrons are "attached" to the atom and possess energy which has certain discrete values or levels. When the energy goes from a higher level to a lower one, the energy difference is radiated at a specific wavelength or line. Conversely, radiation at the same wavelength can be absorbed, raising the electron energy from the lower level back to the higher one.



Three types of spectra showing *continuous emission spectrum, emission line spectrum* produced when electrons attached to an atom go from higher to lower energy levels and give out energy and *absorption line spectrum* produced when continuous spectral radiation is absorbed by electrons attached to an atom and go from lower to higher energies.

The simplest atom is hydrogen consisting of a proton as nucleus and a single electron circulating around it. This electron has many possible energy levels. Its biggest permissible jumps in energy result in the shortest wavelength lines for hydrogen which fall in the ultra-violet part of the spectrum. The lines are called the Lyman series after Theodore Lyman who discovered them in 1905. The longest line of the series, designated Lyman-alpha, has a wavelength of 122 nanometers and the shortest a wavelength of 91 nanometers. Hydrogen also has many other emission lines at longer wavelengths corresponding to smaller energy changes. One group of lines called the Balmer series falls mostly within the visible spectrum and is an important series in the spectra of stars, galaxies and quasars. This series is named after J.J. Balmer, a Swiss physicist who discovered it in 1885.

Hydrogen, with but one electron, has many lines and other atoms, with more electrons, have many more possible energy transitions and correspondingly more emission (or absorption) lines.

Every chemical substance has its own unique pattern of lines, as distinctive as a fingerprint. By matching the lines in the spectrum of a star with ones produced in a laboratory on the earth, an astronomer, working like a detective, can deduce what substances are present in the star.

If an atom receives sufficient energy (as by heating) to be stripped of one or more of its electrons, it becomes ionized. In this ionized state the remaining electrons are still attached to the atom and if they change energy levels they produce a different line spectrum. Thus, lines in the spectrum of a star can reveal not only what kind of atom is producing the radiation but also whether it is ionized (and, hence, whether it is hot or cold).

As the energy-level changes of the electrons increase, the wavelengths may decrease into the x-ray region of the spectrum and if changes occur in the nucleus of the atom, involving even higher energies, gamma rays may result.

In contrast to attached electrons which have discrete energy levels, a free electron can emit over a continuous range of wavelengths. Radiation from a free electron may occur, for example, when it is deflected in passing near another charged particle. The radiation is called *bremsstrahlung* (German for braking radiation) since the electron is slowed by the encounter.

Molecules or combinations of atoms in interstellar space also have emission and absorption lines corresponding to discrete energy transitions related to the molecules' state of vibration or rotation. These include ammonia at 13 millimeters wavelength, hydrogen sulphide at 2 millimeters, water at 14 millimeters, the hydroxyl radical (OH) at 18 centimeters, carbon monoxide at 3 millimeters and ethyl alcohol at 3.5 millimeters.

All objects at temperatures above absolute zero (zero kelvin or minus 273 degrees celsius) radiate electromagnetic waves according to their temperature in what is called *thermal radiation.* They also may absorb such thermal radiation. In general, a good radiator is also a good absorber. Thermal radiation from objects, which are perfect emitters and absorbers, depends on their temperature and the wavelength in a manner first described by Max Planck in 1906.

Thermal radiation curves for objects at temperatures from 3 kelvin to 10 billion kelvin are shown in the accompanying diagram as a function of wavelength. Note that as the temperature increases the peak of the emission moves to shorter wavelengths. We commonly observe this shift when, for example, we heat an iron bar. When the bar becomes warm its infra-red radiation can be felt but not seen. As the bar becomes hotter, it glows visibly red and if hot enough turns white as its peak of radiation moves well into the visible part of the spectrum.

By comparing the radiation from a star at different wavelengths (or colors), it may be possible to deduce its radiation curve (or enough of it) to determine its *temperature* from these radiation curves. For example, if a star is stronger in the blue than in the red we may conclude that it is hotter than 10,000 kelvin (peak of curve to short wavelength side of optical region) but if it is stronger in the red than in the blue it is cooler than 10,000 kelvins (peak of curve to long wavelength side of optical region). Equal red and blue colors would indicate a temperature of about 10,000 kelvins. The sun's temperature deduced in this way is about 6,000 kelvins.

If the star has a sufficiently strong magnetic field, the lines may split, as distinguished from a broadening, into a number of closely-spaced components. The effect is due to the effect of the magnetic field on the atoms of the star's atmosphere. The separation of the component lines is a measure of the strength of the *magnetic field on the star.* The effect was discovered in 1896 by Pieter Zeeman and the phenomenon is referred to as the *Zeeman effect.*

Stars: Their Spectra and Their Evolution

Are all stars alike? No indeed, there are many different kinds. The list is long and their names are intriguing. There are red giants, blue giants, white dwarfs, red dwarfs, yellow dwarfs (our sun is one), infra-red stars, neutron stars (or pulsars), black holes and many more. Stars may also be described as old, young or middle aged, first generation or second generation.

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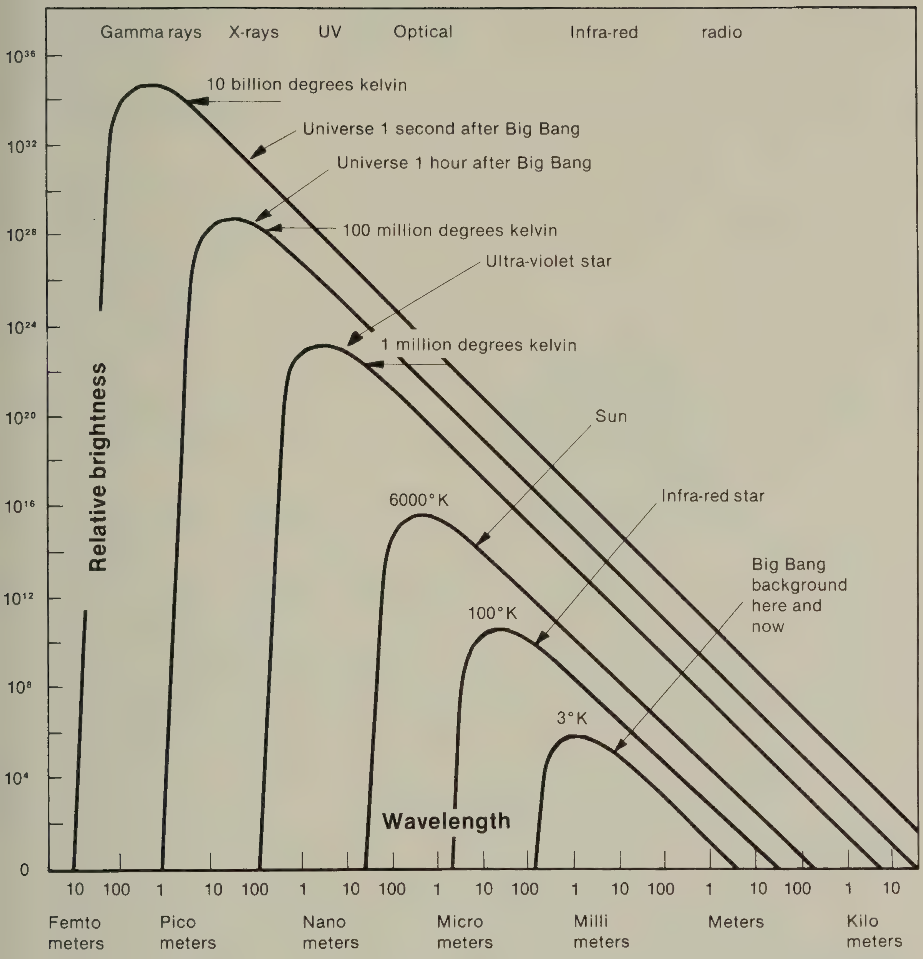
1 kelvin equals 1 degree celsius above absolute zero.



Thermal radiation curves for temperatures from 3 kelvin to 10 billion kelvins (1 kelvin = 1° celsius above absolute zero) as a function of wavelength from radio waves (measured in meters) to gamma rays measured in picometers (pm). The scale is logarithmic. Note that as the temperature increases the peak of the radiation curve moves to shorter wavelengths.

At birth a star is a relatively cool object which emits infra-red rays. After maturing it may spend a long time, measured in billions of years, in a relatively stable state (the sun is at present in this condition). Growing older it may become more unstable and explode as a nova or a super-nova, its remnant collapsing into a white dwarf, a pulsar or a black hole. During its lifetime a single star may be an infra-red star, a yellow dwarf, a red giant and a white dwarf so that many of the different names simply indicate the age or condition of a star.

It is a remarkable achievement that astronomers have been able to learn so much about the age and evolution of stars because stars live for billions of years while our knowledge of them is very brief. The situation is like that of a mayfly, which lives for a day, trying to comprehend the human life cycle from what it can see of a holiday crowd at a picnic. The mayfly is not able to watch a certain infant grow through childhood to maturity. The mayfly must infer that the different sizes and conditions of the humans, whether active or infirm, are indicative of their age. Like a mayfly, the astronomer has inferred from his brief view of the stars something of their age and evolution.

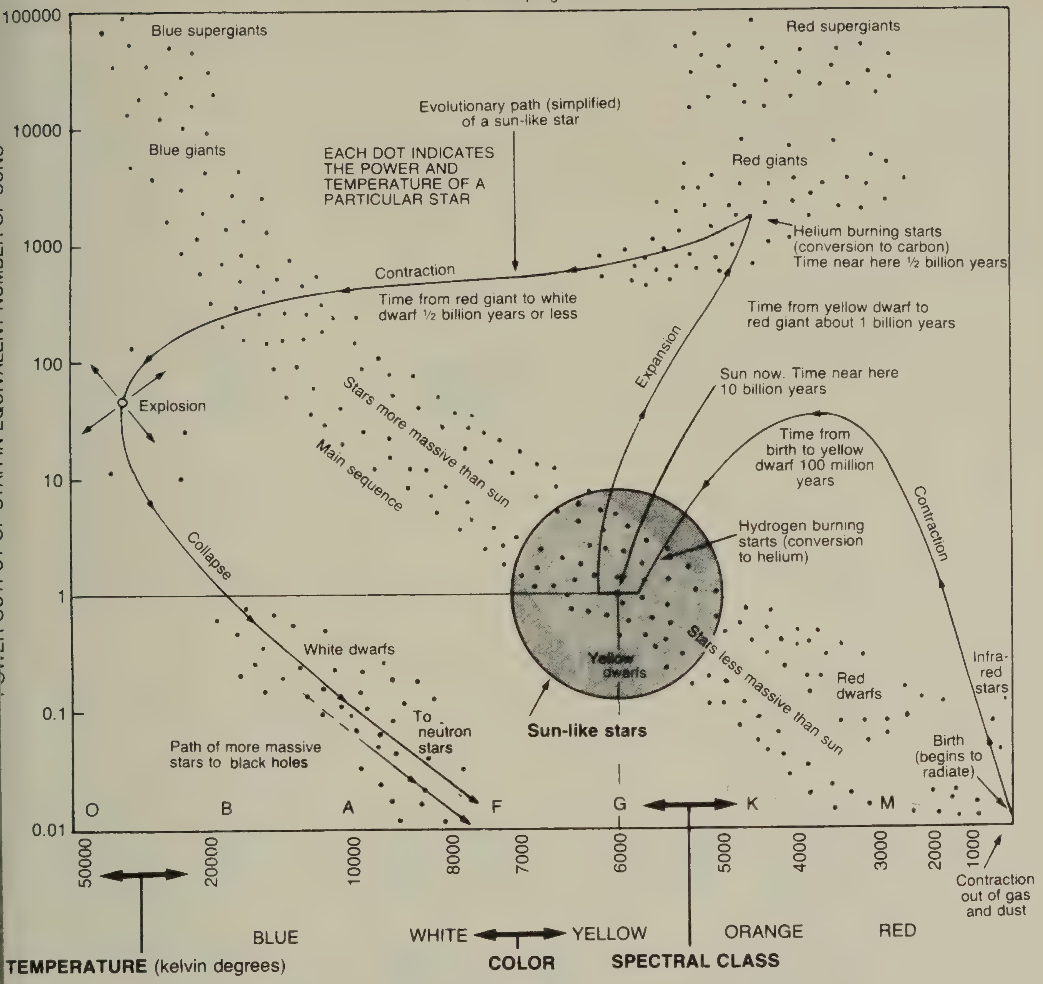
One of the great strides towards an understanding of stars was taken by Enjar Hertzsprung of Denmark and Henry Norris Russell of Princeton in the first decade of this century. Working independently, they studied the relation of the power of stars to their temperature. With the aid of a **Power-Temperature Graph**, often called a *Hertzsprung-Russell diagram,* they found that most stars are in a well-defined region, called the *main-sequence,* extending diagonally from the upper-left to the lower-right of the diagram. There are so many stars on the main-sequence simply because they spend most of their lives there. But there are also stars at other parts of the diagram. Those at the upper-right are relatively cool (red) but very powerful, so they must be very large. They are called *red giants.* The star Betelgeuse is an example. The stars at the lower-left are relatively hot (white) but weak. Therefore, they must be small. They are called *white dwarfs.* The companion star to Sirius is a white dwarf. The sun, with an intermediate temperature of 6000 kelvin degrees, is a yellow dwarf star and is on the main sequence.

From spectral colors and spectral lines, astronomers have classified stars into spectral types covering the color range from blue to red by an arbitrary sequence of letters: O, B, A, F, G, K, M. Hot blue stars are O or B types, cooler red stars are M types. The sun is an intermediate temperature yellow star of the G type.

If one is interested in a Search for Extra-Terrestrial Intelligence (SETI) the spectra of stars can be useful because if one G-type star, the sun, has planets one of which, the earth, has intelligent life, we might do better to search for tell-tale signs of life associated with G-type stars than other types. Thus, the nearer G-type stars have been considered as prime candidates for possible beacon signals. The first star at which Frank Drake

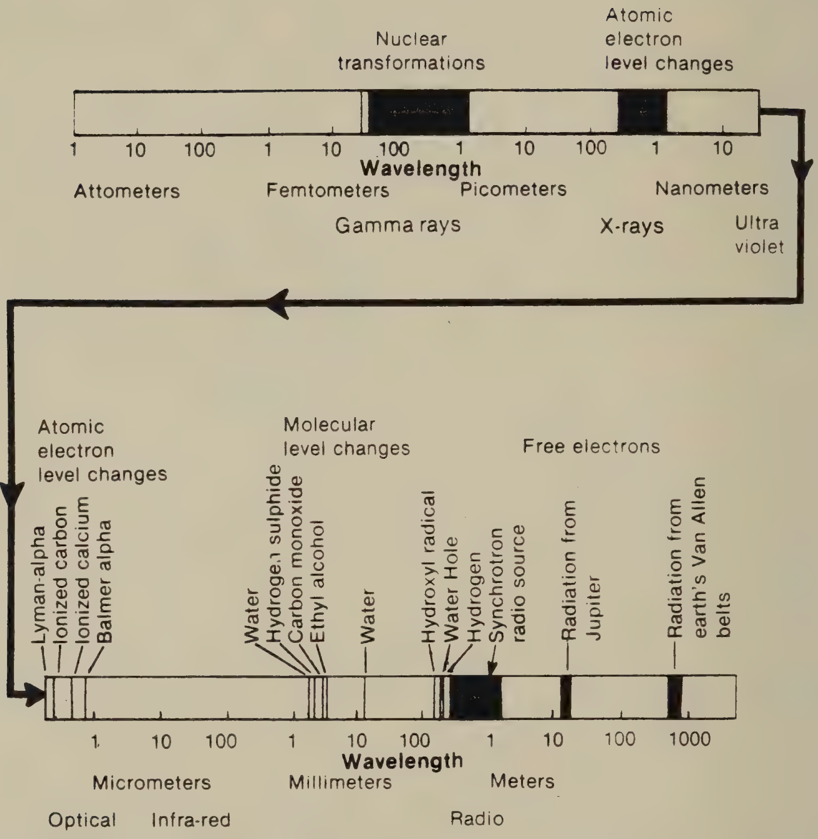
POWER-TEMPERATURE (HERTZSPRUNG-RUSSELL) DIAGRAM

of a sampling of stars

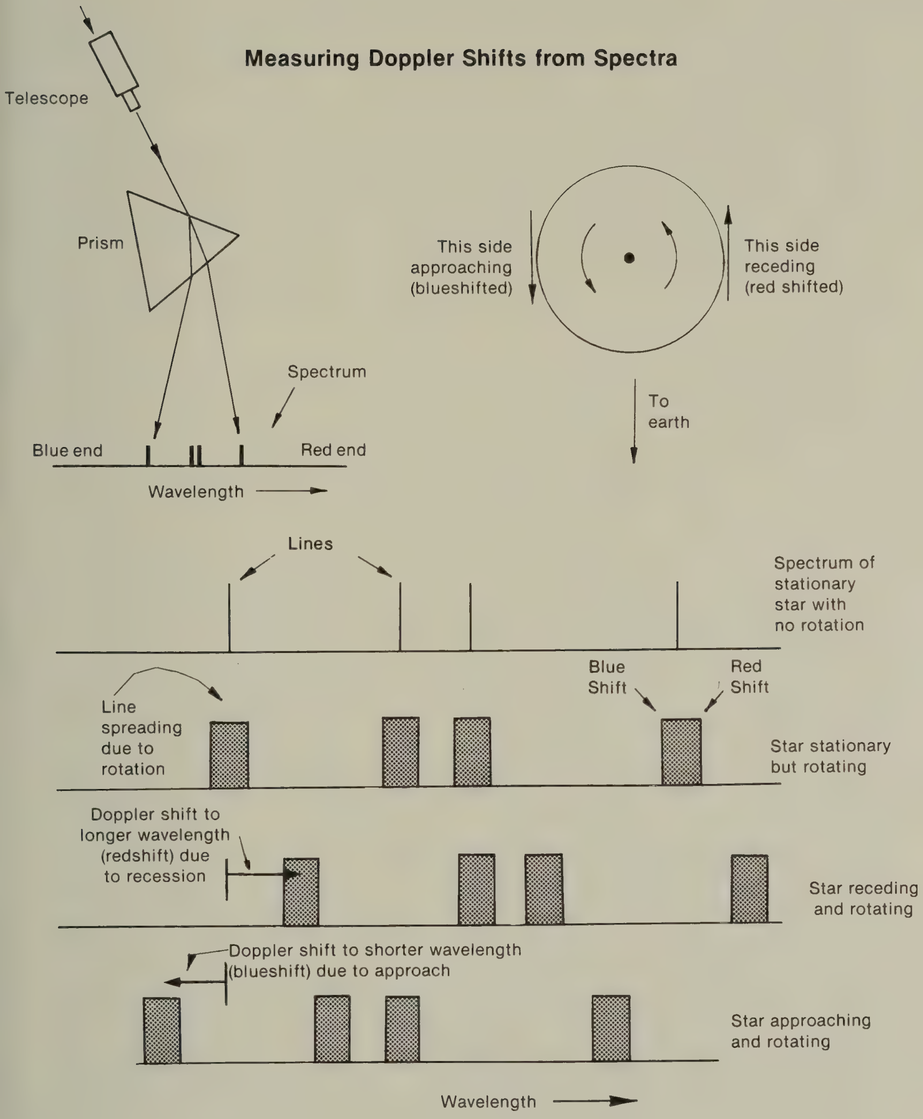


The bottom scales give the temperature in degrees kelvin, the corresponding colors and the spectral class letters. The circle centered on the sun (embracing F, G and K stars of the Main Sequence) includes the sun-like stars which some astronomers regard as the most likely to have planets and some of these even possibly life. A typical star, such as the sun, is about one million kilometers in diameter, a white dwarf about ten thousand kilometers (earth size), a neutron star or pulsar about ten kilometers and a black hole less than one kilometer in size.

If the mass of a star is less than a certain critical value (about 3 times the mass of the sun) it may collapse into a white dwarf or a neutron star (pulsar) but if the mass of the collapsing star is more than this critical value it can only become a black hole.



Lines and continuum emission of the electromagnetic spectrum from gamma rays to radio waves.



Measuring Doppler Shifts from Spectra

The light from a star can be separated into its colors or spectrum with a prism. Spectral lines can indicate rotation (lines *doubled or broadened)* and movement of the star away from us (lines *redshifted,* wavelength longer) or movement toward us (lines *blueshifted,* wavelength shorter). Turn page for more on Doppler effect.

pointed an antenna in his famous Project Ozma, is a G-type star, Tau Ceti. Stars of the spectral types F and K are close enough to G to also be considered as likely candidates. The second star at which Drake pointed his antenna is a K-type star, Epsilon Eridani.

To summarize:

- The temperature of a star is related to its color. Blue stars are hotter than yellow stars and yellow stars are hotter than red ones.
- A star follows a life-cycle during which it may at different times be an infra-red star, a yellow dwarf, a red giant and a white dwarf.
- The elements in a star can be determined from lines they produce in the star's spectrum.
- The sun is a G-type star.
- SETI searches are commonly directed at F, G and K stars because they are somewhat similar to the sun.

The Doppler Effect and the Red Shift

When a rapidly moving vehicle passes with it horn sounding, there is an abrupt decrease in the pitch of the horn. This is the *Doppler effect,* first described by Christian Johann Doppler of Vienna 1842.

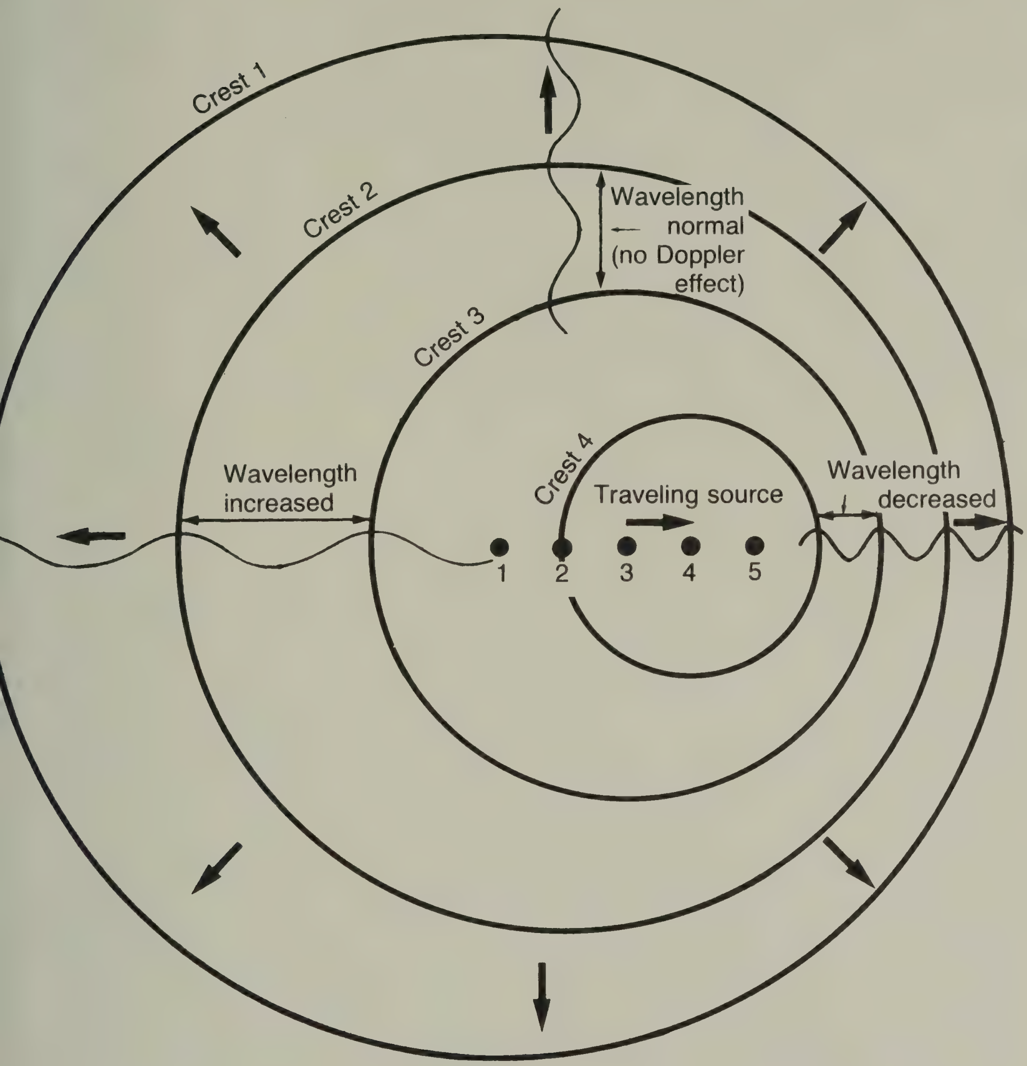
A decrease in pitch (or frequency) corresponds to an increase in wavelength. Thus a receding object has a longer wavelength (or lower frequency) than when it is approaching. The effect can be observed for sound waves, water waves and electromagnetic waves (light and radio waves).

Referring to the **Doppler Effect Diagram**, suppose a source of waves is moving to the right. When it was at position 1, it sent out the crest of a wave, by the time the source reached position 2 it sent out another crest and so on. By the time it reached position 5, the previously emitted crests had expanded to the circles shown. The wavelength (or crest to crest) distance is less in the direction toward which the source is traveling (to the right) and greater in the direction from which it is receding (left). This is the Doppler effect. Perpendicular to the direction the source is traveling, the wavelength is normal (no Doppler effect).

Suppose that the source is sending out a sound wave in air at middle-C. Then an observer to the right hears high-C (wavelength halved), while an observer to the left hears F-below-middle-C (wavelength 50 percent longer).

The change in wavelength due to the Doppler effect is simply related to the wave and source velocity for a sound wave, as in the above example. This is also the case for electromagnetic waves provided the source velocity is small. However, if the source velocity is an appreciable fraction of the velocity of light, the relation is more complex and we would need to take the relativity of Einstein into account in our calculations.

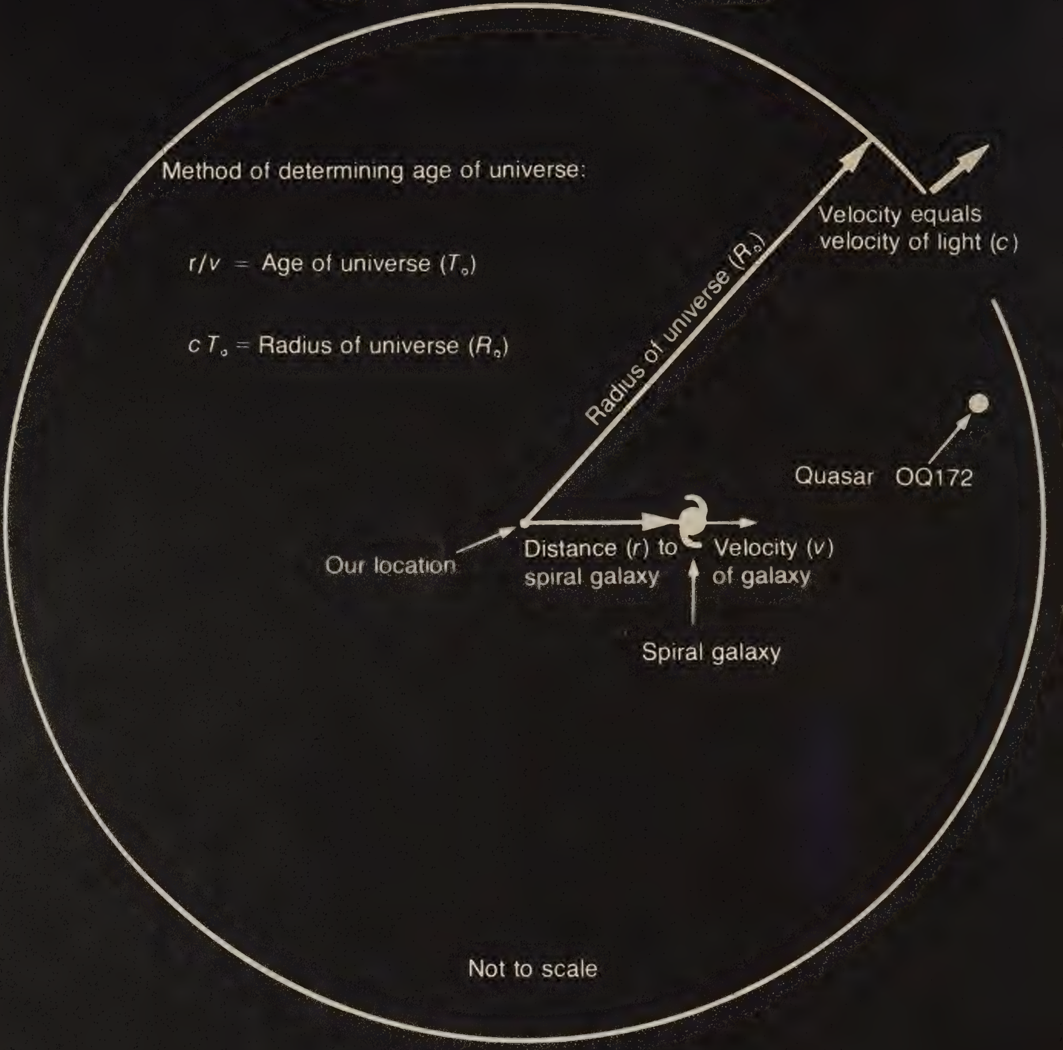
DOPPLER EFFECT DIAGRAM



A source of sound waves (in air) traveling from points 1 to 5 appears to radiate shorter wavelengths in the direction it is approaching (to the right) and longer wavelengths in the opposite direction (to the left). This is the Doppler effect.

In this example, the source is traveling at half the velocity of the sound waves so the wavelength to the right is half the normal wavelength, while to the left it is three-halves (or 50 percent more than) the normal wavelength. Perpendicular to the travel direction of the source (up or down on the diagram), the wavelength is normal (no Doppler effect).

The Expanding Universe


Method of determining age of universe:
r/v = Age of universe (T_o)
cT_o = Radius of universe (R_o)
Radius of universe (R_o)
Velocity equals velocity of light (c)
Quasar OQ172
Our location
Distance (r) to spiral galaxy
Velocity (v) of galaxy
Spiral galaxy
Not to scale

By measuring the velocity and distance of a remote galaxy, the age of the universe can be calculated. The galaxy shown is but one of 100 billion which fill the universe. The further out the galaxy, the higher its velocity away from us, until at the "edge" the velocity reaches a maximum equal to the speed of light. The most distant known object in the universe, quasar OQ172, is also shown. It is receding at 91 percent of the velocity of light and is 91 percent of the way from our location to the "edge" of the observable universe. A quasar is believed to be a galaxy with a dense and powerful nucleus but so far away that it looks like a star, that is, a single point of light. The name quasar is derived from a combination of the words QUASi and stellAR, to suggest that it is a quasi-star, that is, an object which looks like a star but isn't a star.

Chemical elements have characteristic spectral lines at specific optical wavelengths so that an astronomer can tell what elements are present in a star. However, if the star is receding (or approaching) these lines will be shifted to longer (or shorter) wavelengths by the Doppler effect.

If the star is rotating, a line is broadened from its normal condition because some of the light comes from parts of the star which are moving away and some from parts which are approaching. From the amount of the broadening, conclusions may be drawn about the star's rotation.

The distance to some of the nearer stars can be measured by a triangulation method as the earth swings around its orbit. Galaxies are too far to use this method and another technique involving a class of variable stars (Cepheids) is used. The brightness of such a star, some of which can be seen in distant galaxies, is related to its period of variation (whether days or weeks) so that if it is intrinsically bright or powerful (as indicated by its period) but appears faint, we can conclude that it is far away.

About 1930 Edwin Hubble was able to determine the distance of a number of galaxies by observing some of the Cepheid variable stars they contained. Hubble used the 2.5-meter Mt. Wilson, California, telescope which at that time was the largest in the world. Hubble also noted that there was a shift in the spectra of the light from the galaxies to longer or redder wavelengths by an amount which increased with the distance of the galaxy. Interpreting this ''redshift'' as due to the Doppler effect, indicated that the galaxies were rushing away from us at velocities which increased with their distance. This led to the idea of an *expanding universe,* and by extrapolation backwards in time, to its origin from an initial explosion or *Big Bang* from which it has been expanding ever since.

To summarize:

- The Doppler effect is useful for determining the velocity of approach or recession of moving objects.
- Wavelengths are stretched out or longer when a wave-producing object is receding.
- Wavelengths are compressed or shorter when a wave-producing object is approaching.
- The wavelength of light from distant galaxies is increased making it redder. This *redshift* of the light may be interpreted to mean that the galaxies are receding from us.

Age of the Universe Table

(Small Hubble constant, old universe; big Hubble constant, young universe)

Hubble constant (in hubbles*)	Radius of universe (in billions of light-years)	Age of universe (in billions of years)
50	20	20
67	15	15
100	10	10

* One *hubble* equals one kilometer per second per megaparsec where one megaparsec equals 3.26 million light-years. The table values for the radius and age of the universe are nominal round-offs.

The radius R_0 of the universe equals the velocity of light divided by the Hubble constant H_0 ($R_0 = c/H_0$). The age of the universe in years is numerically equal to the radius of the universe in light-years. A convenient relation is that the age of the universe T_0 in billions of years is approximately equal to 1000 divided by the Hubble constant in hubbles (or $T_0 = 1000/H_0$).

A Hubble constant of 100 hubbles implies that a 10 meter radial length stretches 1 millimeter longer in one million years. Thus, we may express 100 hubbles as 1 millimeter per million years per 10 meters.

Numerical example: Suppose a galaxy at a distance of 1.5 billion light-years is receding at one-tenth the velocity of light (one-tenth light-year per year). Then, dividing distance by velocity, we obtain 1.5 billion times 10 or 15 billion years as the age of the universe.

The Age of the Universe

How old is the universe? Assuming the universe has expanded uniformly since the Big Bang, we can determine its age if we can measure the velocity of recession of a remote galaxy and also its distance. Dividing the distance by the velocity gives the age of the universe. Measurements of many other galaxies should all give about the same age. Multiplying this age by the velocity of light gives a distance we call the radius of the observable universe.

The reciprocal of the age of the universe is called the "Hubble constant", after Edwin Hubble, the father of the expanding universe idea. Turning it around, the reciprocal of the Hubble constant equals the age of the universe. Thus, the smaller the Hubble constant, the older the universe.

In my textbook, "Radio Astronomy" (McGraw-Hill) published in 1966, I state:

"*The correct value for the Hubble constant is uncertain.* A nominal value in wide present-day (circa 1965) usage is 100 kilometers per second per megaparsec. Values between 180 and 75 have been used during the past decade (corresponding to ages of about 5 to 13 billion years)."

Using the 100 kilometer value yields an age for the universe of about 10 billion years.

In the years after my book was published, astronomers reported lower and lower values of the Hubble constant until more recently it was thought to be only half as large implying a universe 20 billion years old. However, very recently other astronomers have reported observations indicating a Hubble constant of almost 100 putting us back again to 10 billion years.

The apparent uncertainty in the Hubble constant is not surprising since the great distances involved cannot be measured directly but must be estimated by indirect, roundabout methods which may be ambiguous. Astronomers are simply groping and working their way toward a more certain value.

The *velocity* of recession of a distant galaxy (as determined from its redshift) divided by its *distance* gives a value for the Hubble constant. If further and further galaxies could be measured the *velocity* would approach the velocity of light and the *distance* the radius of the observable universe but, for uniform expansion, the ratio, or Hubble constant, should remain the same, that is, be what its name implies: a constant.

Will astronomers agree on 10 billion years or will it be 20? The controversy may go on for years. In the meantime we will take 15 billion as a nominal value for the age of the universe (and 15 billion light-years for its radius).

A "Guest Star" Appears

Almost a thousand years ago an awesome event was witnessed by a Chinese court astrologer. His account, which has fortunately been preserved, relates the sudden appearance of a bright new "guest star" in the heavens in July 1054 A.D. For many nights its brilliance was dazzling. It was, in fact, so bright that it could even be seen in broad daylight. Gradually, over days and weeks, its brilliance decreased and the astrologer noted that his "guest star" had departed.

The astrologer had never seen anything like it before. Surely it must be an important sign, an omen, a portent of profound significance. Every clear night for years he had climbed the winding stone stairs to the open top of the high tower of his emperor's palace to search the sky for omens. The moon and planets he knew well. To him they were animals he called by name who wandered to and fro on their regular rounds. The stars and their constellations, too, were all old friends. Of the meteors and fireballs which flashed across the sky he took due note. To him they foretold of bandits who would infiltrate the province. His greatest interest was in the comets, those huge mysterious couriers trailing long plumes which appeared for a few weeks and then vanished. Their appearance meant that a great battle was imminent. But the new "guest star", brighter than any in the entire firmament, was to him an especially important message bearer, foretelling perhaps of a new era for the emperor's realm.

Invisible to the emperor's astrologer was an explosion cloud which grew where the star had been. As it expanded outwards over the centuries it took on the appearance of a wispy, glowing, pinkish mass like a tuft of cotton candy, visible only with the aid of a telescope. Its faint, diffuse form could be easily mistaken for the dim, blurred head of a comet.

In 1784 the great French comet hunter Charles Messier made it number one in a list of a hundred such nebulous objects which he compiled for the convenience of comet hunters. Comets move with respect to the stars. The objects in Messier's list did not. Thus, if a comet hunter discovered what he thought was a comet he checked Messier's list. If the object was at the position of one of Messier's objects he didn't need to waste time observing it night after night to see if it moved but could continue his searching elsewhere.

In 1844 Lord Rosse's big 1.5 meter telescope revealed the object in splendid detail and Rosse named it the Crab nebula for its resemblance to the spiny crustacean. Now it had two names: Messier Number 1 (M1 for short) and the Crab nebula.

To the Chinese astrologer in 1054 the Crab nebula was a "guest star", an omen. To Charles Messier in 1784 it was an object not to be confused with a

The “guest star” of 1054 A.D.

comet. To Lord Rosse in 1844 it was the Crab nebula. But neither Messier nor Rosse connected it with the guest star of 1054 A.D. because references to the star were buried in obscure oriental chronicles.

Then, in the 1930s John Duncan of Wellesley College noted that the nebula was expanding and he measured the rate. Projecting the expansion backwards made the nebula converge to a point near 1054 A.D. Finally, in 1942, Dutch astronomers searching old Chinese records made the connection with the guest star of 1054 A.D.

In 1948 John Bolton in Sydney, Australia, with a radio telescope he and Gordon Stanley had built, discovered that the Crab nebula was a strong radio source. It was the first radio source, other than the sun, to be identified with an optical object.

Then, in 1968, a year after the first pulsar was discovered, pulsing radio signals were detected coming from the center of the Crab nebula at a rate of 30 pulses per second. Within a year the pulsing source was identified with an optical star and Joseph Miller and Joseph Wampler of Lick Observatory dramatically demonstrated that all of the light of the star was blinking off and on.

The star had been studied for many years because of its unusual optical properties and it had been recognized as early as 1942 that it was the remnant of an exploded star or supernova, but no one had suspected that it was blinking (the rate is too fast for the blinking to be detected readily with the eye or ordinary astronomical cameras.) Further observations with other kinds of telescopes subsequently revealed that the star is pulsing 30 times a second, not only at radio and optical wavelengths, but also at infra-red, x-ray and gamma ray wavelengths. Thus, the relic of the 1054 A.D. "guest star" turns out to be a most versatile pulsar!

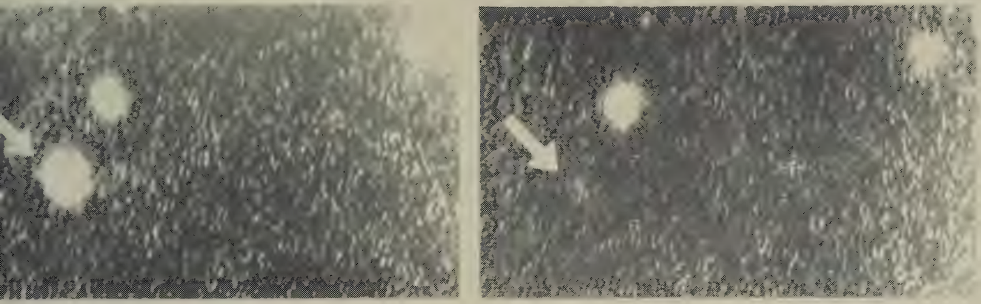
The Crab nebula and its pulsar are at a distance of about 5000 light-years. This means that although the explosion was observed on the earth in 1054 A.D. it had actually occurred some 5000 years earlier.

A sequence of events could now be postulated. As the star, perhaps a million kilometers in diameter, exhausted its nuclear fuel there was an explosion which blew off part of the star's mass producing the brilliant spectacle of the guest star. The explosion cloud from the star expanded over the years to form what we now observe as the Crab nebula. What remained behind of the star collapsed under its own gravitational attraction to form a core only a few kilometers in diameter but as massive as a million earths. While shrinking in size it also speeded up in rotation, like a pirouetting figure skater, to some 30 revolutions per second, due to conservation of momentum. This core or relic is the Crab pulsar radiating at wavelengths from gamma rays to radio waves. As it radiates away its energy it is very gradually slowing down. This oversimplified scenario summarizes what we now know and future observations will serve to confirm, amplify or revise it.

It is nearly a thousand years since the "guest star" appeared to the Chinese astrologer. What will be learned in the next thousand years? Will advances in mankind's understanding of the Crab nebula make our present knowledge seem as inadequate as the ancient astrologer's now seems to us?

Note: The old Chinese chronicles describing the guest star of 1054 A.D. involve some contradictions and discrepancies so that it is not possible to conclude with complete certainty that it marked the origin of the Crab nebula. A connection, however, appears probable.

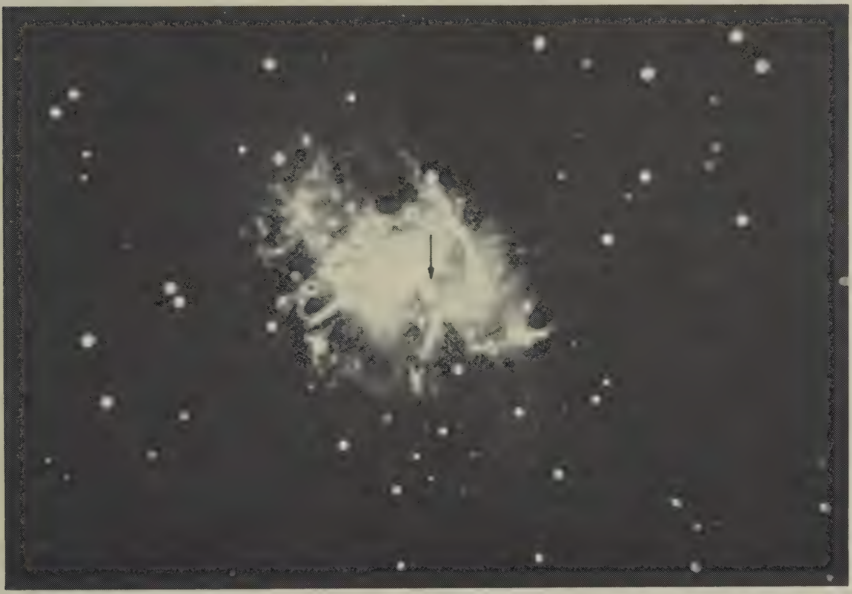
The Crab nebula pulsar



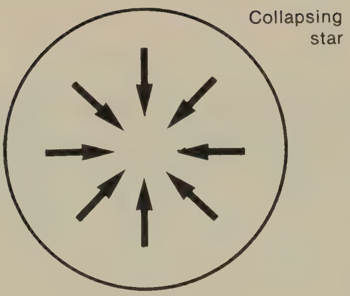
Now you see it

Now you don't

The star the ancient Chinese astrologer saw explode now blinks on and off 30 times per second. In the photograph at the left, the star (arrow) is on; in the photograph at the right it is off. (Photographs courtesy of Joseph Miller, Lick Observatory).

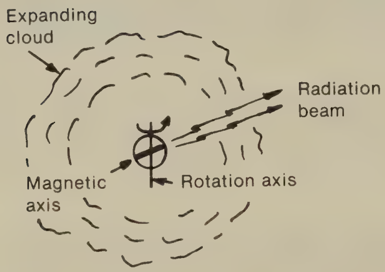


The billowing, fluffy cloud blown off from the star which exploded in 1054 A.D. The star (arrow) is now a rapidly spinning pulsar. It is the fastest known pulsar in the sky. The cloud or nebula (object number one in Messier's catalog) is what astronomers call a supernova remnant. An explosion producing one (as in 1054 A.D.) is a rarely observed event. However, two European astronomers were fortunate to witness similar explosions. Tycho Brahe reported seeing one in 1572 and Johannes Kepler another in 1604 A.D. (Photograph courtesy of Joseph Miller)



When its nuclear fuel is depleted, a slowly turning star one million kilometers in diameter collapses under its own gravity

to



a rapidly-spinning, super-dense neutron star a few kilometers in diameter. It sends out a beam of radio waves which sweeps as it turns, like a lighthouse beam, making it a pulsar.

Our knowledge of the cosmos is dependent on our instruments — our telescopes of all kinds. To appreciate them we need to understand a few basic principles.

Refracting and Reflecting Telescopes

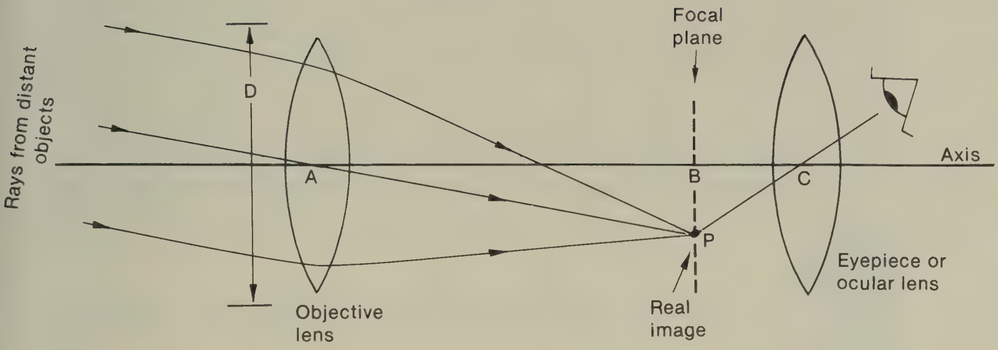
Galileo's telescope used lenses, Herschel's employed mirrors. Both kinds are used today but more importantly, optical telescopes have become bigger and better.

Lens telescopes are called *refractors* and mirror telescopes are called *reflectors.* In a refracting telescope, rays from a distant object are bent or refracted as they pass through an *objective lens* and brought to a focus at a point, P, forming a *real image.* This image can be recorded by a photographic plate placed at the focus (along the focal plane BP).

To view the image by eye, an *ocular or eyepiece lens* is added. The eyepiece permits viewing of the image formed in the focal plane. It also provides a magnification in proportion to the ratio of the distance AB between the objective lens and the focus and the distance BC between the eyepiece and the focus.

The first reflecting telescope was designed by James Gregory in 1663 but it remained for Isaac Newton to construct the first one in 1672. Rays from a distant object are reflected by a parabolic mirror and brought to a focus at a point, P. A photographic plate may be placed at this position (along the focal plane BP) to record the image.

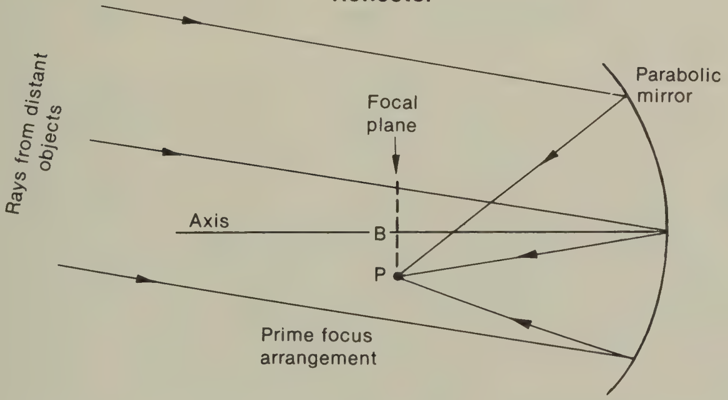
Refractor



In a *refracting telescope* rays are refracted or bent by an objective lens and brought to a focus at *P* where a real image of the distant object is formed. This image may be recorded on a photographic plate placed at the focus or it may be viewed by eye with the aid of another lens (ocular or eyepiece).

The *magnification* can be made arbitrarily large by increasing *AB* in relation to *BC*. (Magnification = *AB*/*BC*). However, the useful magnification is limited by the diameter, *D*, of the objective lens. If *D* is not large enought for two points of light to be resolved, no amount of magnification will resolve them. The unresolved image merely becomes larger and fuzzier. A certain amount of magnification is needed for comfortable observing but too much is undesirable.

Reflector



In a *reflecting telescope* rays are reflected from a parabolic mirror and brought to a focus at *P* where a photographic plate may be placed to record the image.

A single lens or refractor does not bring all colors or wavelengths to a focus at the same point. A reflecting telescope can be free of this defect.

For viewing by eye, sub-reflectors may be placed to focus the rays through a hole in the parabolic mirror (Cassegrain arrangement) or to focus them to one side (Newtonian arrangement). The basic configuration is, by contrast, called a prime focus arrangement. Photography can also be accomplished with the Cassegrain and Newtonian telescopes by placing photographic plates at the focal points, P.

Telescope Mountings

The lenses and mirrors of an optical telescope are commonly mounted inside a cylindrical frame or tube. By supporting the tube so it can be turned on two perpendicular axes, the telescope can be conveniently pointed anywhere in the sky. Although telescope mountings may differ as to details, the basic motions may be illustrated by a yoke-spindle mounting. With the spindle axis vertical, rotating the tube on the yoke axis raises and lowers the telescope in elevation or *altitude* while rotating it on the spindle axis rotates it horizontally or in *azimuth.* This arrangement is called an altitude-azimuth or *alt-azimuth mounting.*

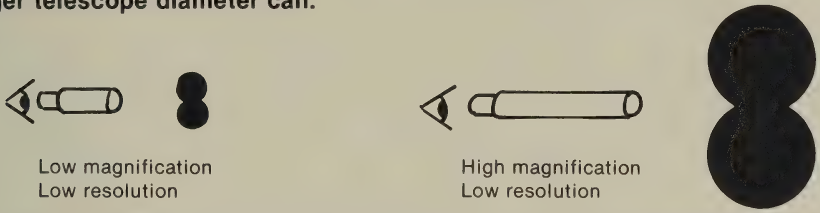
If the spindle axis is set parallel to the earth's axis, the arrangement is called a polar or *equatorial mounting.* The convenience of this mounting is that by turning the spindle shaft at the same rate as the earth turns on its axis (but in the opposite direction) the telescope can remain fixed on a particular star. To stay on a star and follow it across the sky in this way with an alt-azimuth mounting requires simultaneous motions about *both* yoke and spindle axes.

Under computer control this 2-axis motion is no significant disadvantage. Structurally, the alt-azimuth mounting is more straightforward and satisfactory and for these reasons nearly all large radio telescopes have alt-azimuth mountings. The Mt. Pastukhova 6 meter telescope and the Mt. Hopkins Multiple-Mirror-Telescope are examples of large optical telescopes with alt-azimuth mountings. Many early optical telescopes, such as Herschel's, were alt-azimuth mounted. At two points on the earth (north and south poles) an alt-azimuth mounting is identical with an equatorial mounting since at the poles a vertical axis is coincident with the earth's axis.

Motion of an equatorially-mounted telescope around its spindle axis moves the telescope in hour angle. This is an east-west motion in the same direction as the equatorial coordinate called *right ascension.* Motion around the yoke axis moves the telescope in a perpendicular coordinate direction called *declination.*

An observer with a larger diameter telescope can distinguish between closely-spaced objects more readily than an observer with a smaller diameter telescope. It is said that the larger telescope provides better *resolution.*

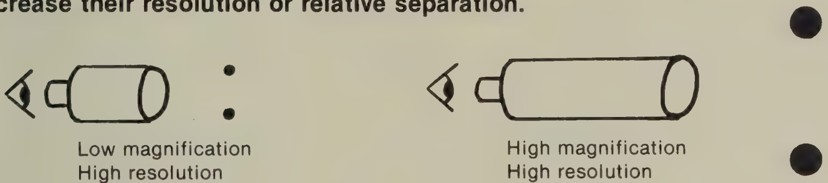
Magnification, which is so important in microscopes, is of secondary importance in telescopes. Thus, no amount of magnification can make closely-spaced objects more easily distinguished from each other but a larger telescope diameter can.


Low magnification
Low resolution

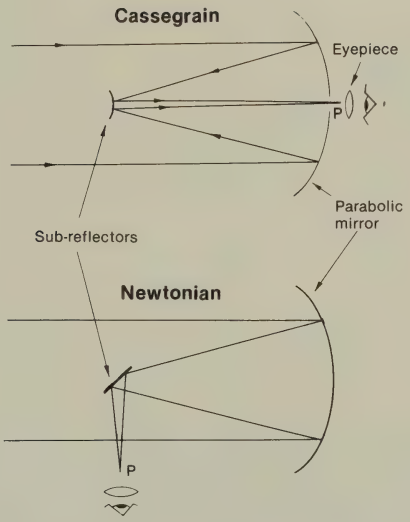
High magnification
Low resolution

Two closely-spaced objects seen under low and high magnification but a low resolution (above) and at higher resolution (below).

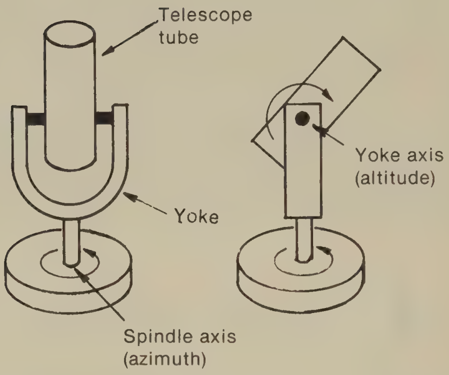
Magnification makes the objects appear larger but it does not increase their resolution or relative separation.


Low magnification
High resolution

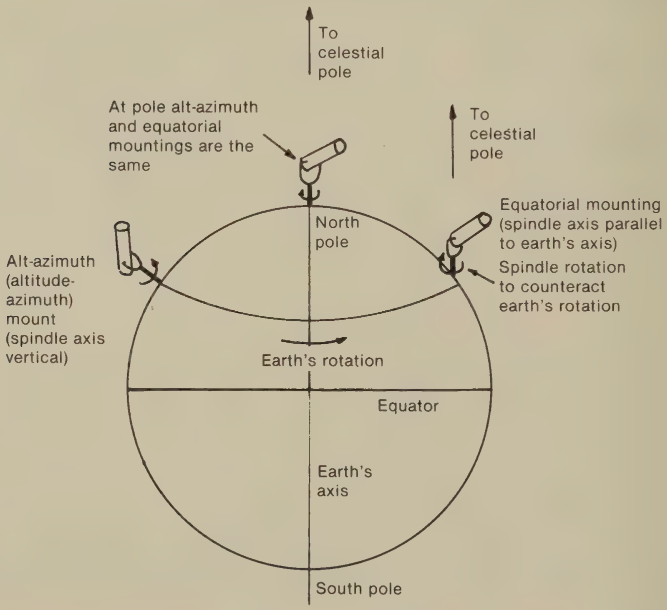
High magnification
High resolution



For viewing by eye with a reflecting telescope the rays may be brought out through a hole in the mirror (Cassegrain system) or reflected to one side (Newtonian arrangement). A variant of the above is the Coude arrangement in which the rays are brought out to a focus through the axis of the telescope mounting.



Basic altitude-azimuth or *alt-azimuth telescope mounting.* The horizontal axis allows motion in altitude or elevation and the vertical (spindle) axis motion in the horizontal or azimuth direction.


To celestial pole
At pole alt-azimuth and equatorial mountings are the same
To celestial pole
Equatorial mounting (spindle axis parallel to earth's axis)
Spindle rotation to counteract earth's rotation
Alt-azimuth (altitude-azimuth) mount (spindle axis vertical)
North pole
Earth's rotation
Equator
Earth's axis
South pole

In the basic *equatorial mounting* the spindle axis is set parallel to the earth's axis. Rotation of the telescope around this axis at the same rate as the earth's rotation (but in the opposite sense) can keep the telescope trained on a star. Equatorial and alt-azimuth mountings are compared in the figure. At the earth's pole the two mountings are the same.

The 5-meter Mt. Palomar Telescope

The 5-meter reflecting telescope on Mt. Palomar, California, was the world's largest optical telescope for over two decades following its dedication in 1948. Named the Hale Telescope in honor of George Ellery Hale, who died 10 years before, it marked the culmination of years of effort by him and many others to produce a truly awesome instrument of giant proportions.

The Rockefeller Foundation supplied the California Institute of Technology the $6.5 million used for building the telescope. At its dedication, Raymond Fosdick, Rockefeller Foundation president, pointed out that,

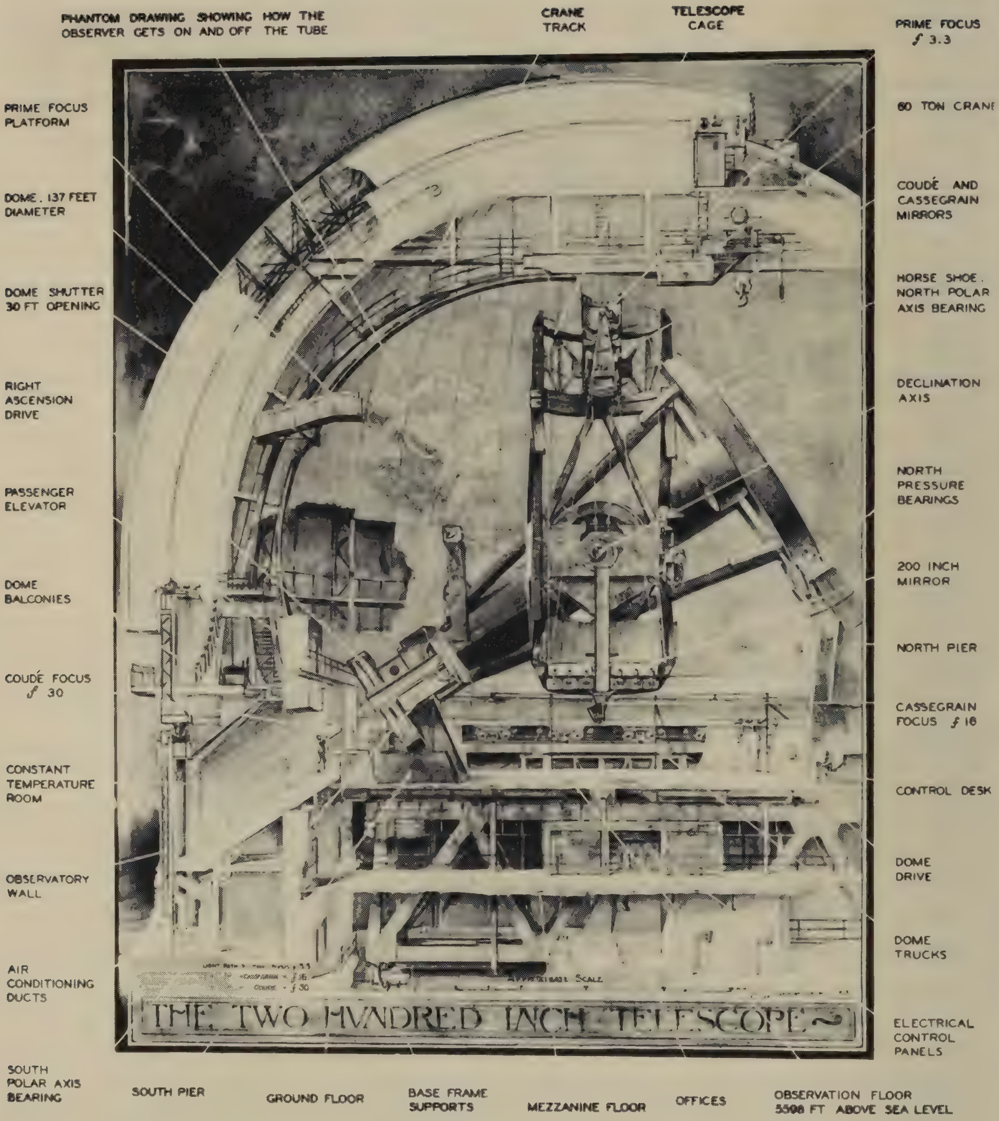
''Adrift in a cosmos whose shores he cannot even imagine, man spends his energies in fighting with his fellow man over issues which a single look through this telescope would show to be utterly inconsequential.''

Fosdick referred to the telescope as the lengthened image of man at his best. ''It is man,'' he said, ''on tiptoe reaching for relevancy and meaning.'' He commented further that there is nothing which lends such dignity to man as the urge to bring the vast illimitable complexity of the cosmos within the range of human understanding. ''In the last analysis'', he concluded, ''the mind which encompasses the universe is more marvelous than the universe which encompasses the mind.''

The 5-meter telescope is an equatorially-mounted instrument, that is, its axis is parallel to the earth's axis. It has a large horse-shoe-shaped open yoke at the north end so that the telescope tube can be swung into it for observing in the direction of the north celestial pole. The moveable parts weight 500 tons and float on a film of oil forced under pressure through bearing pads.

Can we calculate how faint an object this huge telescope can detect? Yes, easily. The telescope diameter of 5 meters equals 5000 millimeters. For easy figuring let us assume the eye's pupil diameter is 5 millimeters. Thus, the Mount Palomar mirror diameter is 1000 times greater than that of the pupil. The light gathering ability of the eye or the telescope mirror is proportional to its *area* so the light collecting aperture of the Mount Palomar telescope is 1000 squared or 1,000,000 times greater. Therefore, the 5-meter Mount Palomar telescope should be able to detect a star only one-millionth as bright as the weakest naked-eye star.

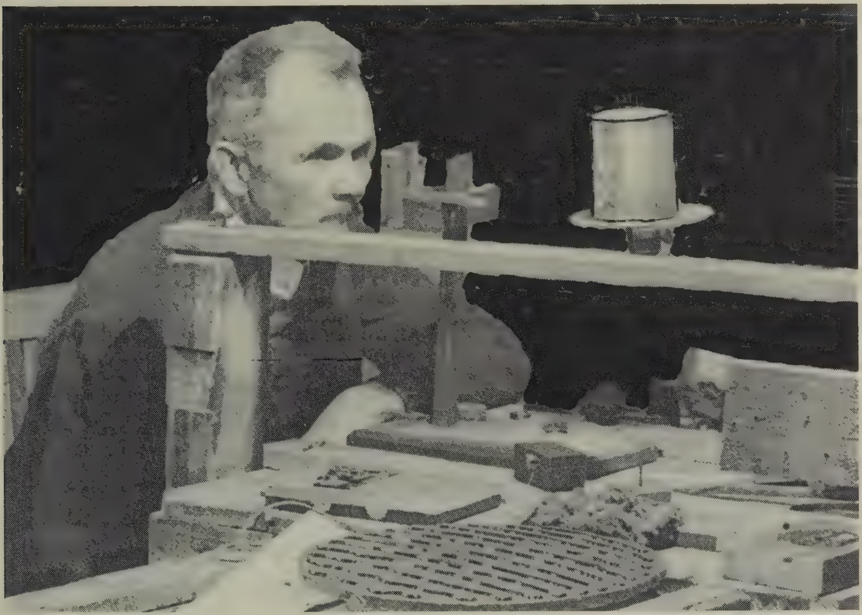
In astronomer's jargon the weakest naked-eye star is about 7th magnitude. Since there are 5 magnitudes per a 100 fold change in brightness, or 15 magnitudes for a 1,000,000 change, the Mount Palomar telescope should be able to reach a 22nd magnitude star ($7 + 15 = 22$). A 3 millimeter pupil diameter for the human eye as used earlier is probably more realistic than the 5 millimeters we assumed above. On this basis the telescope would be somewhat more sensitive and able to reach about one more magnitude or 23rd magnitude. This comparison assumes visual observation with the telescope. Actually it is used mostly with photographic



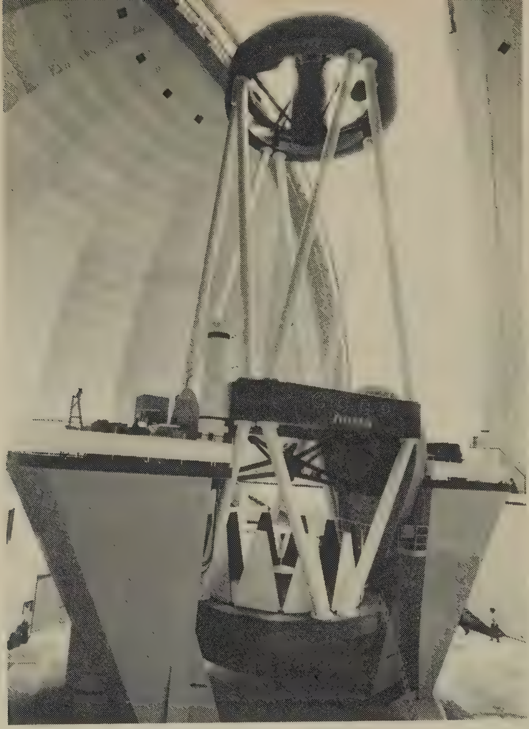
The Mt. Palomar 5-meter telescope (drawing by R.W. Porter) films or other detection devices, sometimes with long exposures. These techniques increase the telescope's sensitivity a great deal further.

What is the maximum possible resolution of the telescope? For green light (500 nanometers) the telescope diameter is 10 million wavelengths. Hence, the resolution angle is 60° divided by 10,000,000 or 6 millionths of a degree. This amounts to about 0.02 arc seconds. This is the angle subtended by two points one centimeter apart as seen from a distance of 100 kilometers. On the earth the atmosphere prevents the realization of such resolution.

While well-suited for observing single stars and small regions of sky the 5-meter telescope does not have a big field of view, that is, objects not close to the central axis of the telescope are not in sharp focus. This is characteristic of the off-axis operation with a parabolic mirror and is a limitation of this type of instrument.

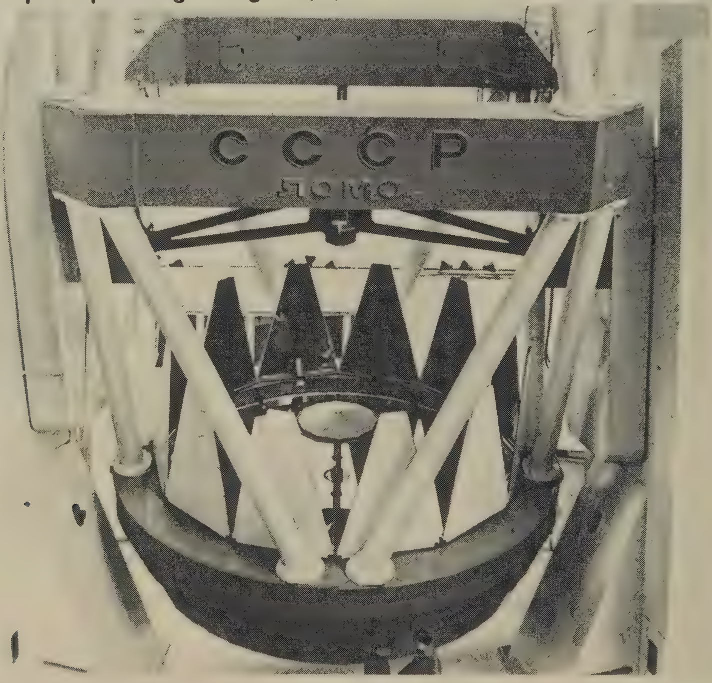


Bernhard Schmidt making a Foucault test of one of his spherical mirrors (out of picture to right). In the Foucault test, devised by Jean Bernard Leon Foucault of the Paris Observatory in 1859, a point source of light is placed at the center of curvature of the mirror (twice the focal distance) and the image is scrutinized with the aid of a knife edge to reveal those areas of the mirror that are "too high" and need further grinding or polishing. Schmidt's light source is in the metal can before him. The circular grinding (lapping) tool resting on the box in the foreground is approximately the diameter of the mirror he is testing. (Courtesy of A.A. Wachmann).



World's largest optical telescope on Mt. Pastukhova, U.S.S.R. with 6-meter diameter mirror. Note person at lower right for scale.

The 6-meter mirror with the petals of the protective mirror cover raised. Note men at bottom of figure. In this view and the one above the telescope is pointing straight up (at the zenith). (Tass from Sovfoto).



The Schmidt Telescope

To make efficient use of the 5-meter telescope a sky survey was needed. So as a working companion of the 5-meter instrument, a 1.2 meter Schmidt telescope was also constructed on Mount Palomar. With this telescope clear, sharp images over at least a 6 degree diameter field can be obtained and thousands of photographs have been taken covering much of the sky. Objects of interest discovered in this survey could then be examined in more detail with the 5-meter telescope.

The Schmidt telescope has a spherical instead of a parabolic mirror. This type of telescope was invented by Bernhard Schmidt, a German telescope maker, to overcome the narrow-field limitation of parabolic-mirror telescopes.

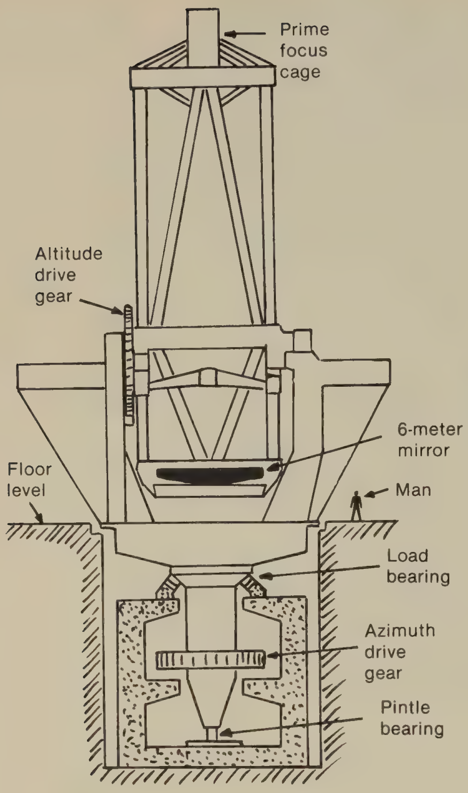
For years Schmidt had been aware of the fact that telescopes with parabolic mirrors produced sharp, round star images only over a small angle or region at the center of the field of view. Spherical, instead of parabolic, reflectors were not used in telescopes because the image was highly distorted by a condition called spherical aberration. But Schmidt recognized that, although distorted, the image was the same over a wide range of angles because a spherical reflector is not angle dependent. If somehow the spherical aberration could be corrected, he reasoned, the spherical mirror might provide the desired sharp images over wide angles.

By 1930 he had formulated an ingenious design in which a glass corrector plate of variable thickness was placed in front of a spherical mirror. The plate was effective in eliminating the spherical aberration. Schmidt constructed a very successful working model with a 44 centimeter diameter mirror giving sharp images over a 15 degree field, an unprecedented achievement. Schmidt died in 1935.

Schmidt's telescope has been hailed as the greatest advance in astronomical optics in two hundred years, yet it is ironical that Schmidt never received an order to build one. His design revolutionized telescope making and Schmidt telescopes, as they are called, have become very popular, providing photographs with sharp, round images over large fields of view many degrees in angular diameter.

The 6-meter Mt. Pastukhova Telescope

The world's largest optical telescope is on Mount Pastukhova rising in the Caucasus Mountains above the eastern shores of the Black Sea not far from the village of Zelenchukskaya, U.S.S.R. The reflector mirror of the recently completed telescope is 6 meters in diameter and weighs 42 tons. Designed by Bagrat Konstantinovich Ioannisiani of the Leningrad Optical Mechanical Organization (LOMO), the telescope has an alt-azimuth mounting which is controlled by an electronic computer. Moving parts weigh 800

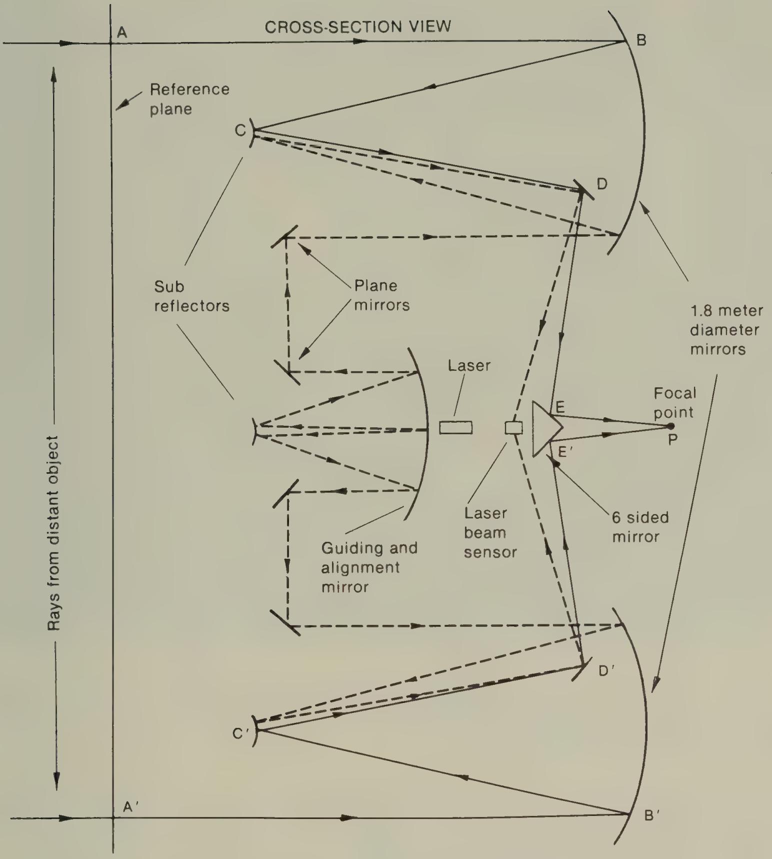


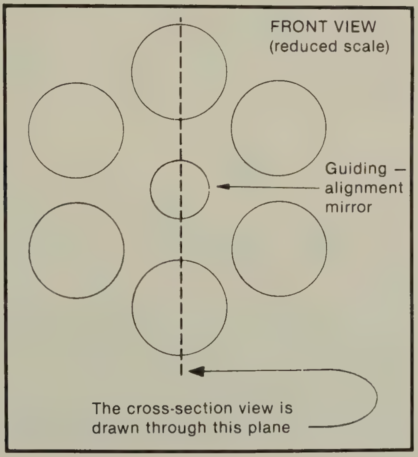
The 6-meter telescope has an alt-azimuth mounting with the spindle axis vertical. The main bearings for this axis are below floor level as indicated in the cross-section view. In this view the telescope is pointing straight up (at the zenith).

tons. The telescope has an alt-azimuth mounting (spindle axis vertical) with bearings located below floor level.

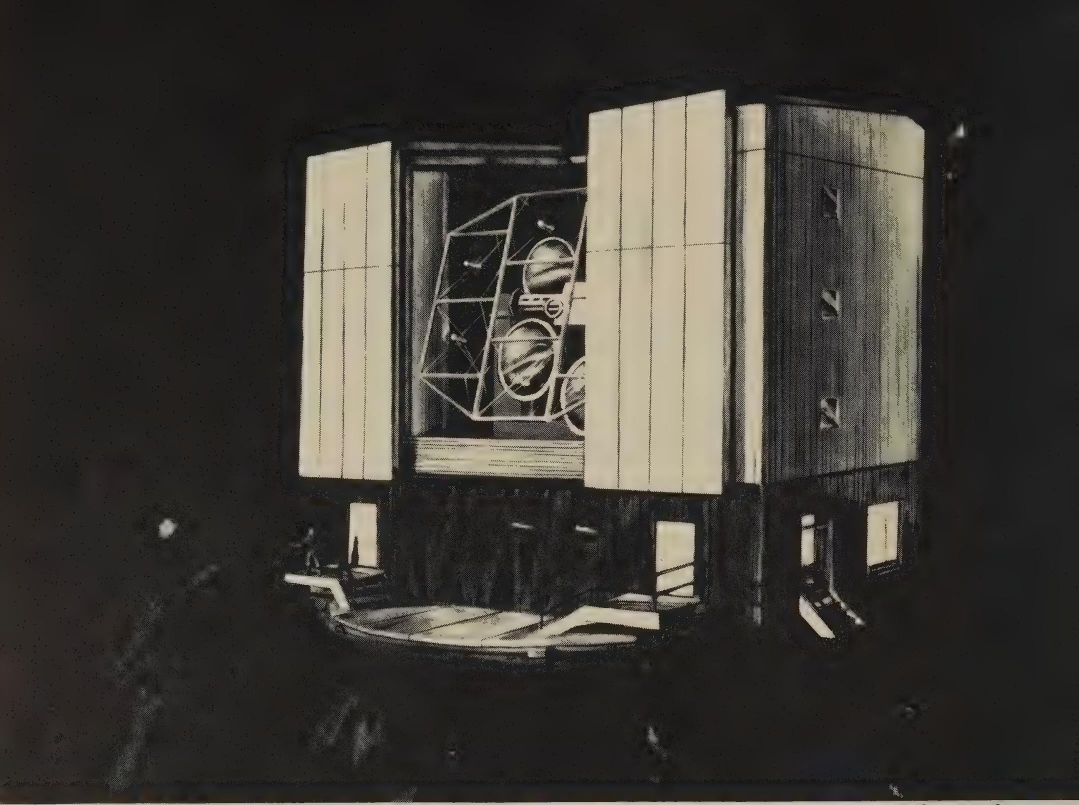
The Multiple-Mirror Telescope

Must a telescope mirror be in one piece or might it consist of a cluster or mosaic of several smaller mirrors? In a solar furnace where the sun's rays are used to heat an object, the idea works well because the focusing of different mirrors only needs to be accurate enough to bring the rays onto the object. However, to faithfully record images on a photographic plate requires that the mirrors be maintained in position to an accuracy of a small fraction of a wavelength. This is a much more severe requirement but with the advent of lasers and electronic computers it can be done. The multiple mirrors have the advantage of lower cost. For example, four 1 meter diameter mirrors have the same total aperture area as a single 2 meter diameter mirror but can be produced at a lower total cost. To maintain alignment requires that the path lengths of rays from a distant object to the focal point (path lengths ABCDEP and A′B′C′D′E′P) must be equal to within a small fraction of a wavelength (solid rays). Ordinary light consists of a mixture of many different wavelengths. In a laser, however, light of essentially a single wavelength can be produced. By transmitting a laser beam via each mirror (dashed rays) to a sensor the path lengths to each mir-




FRONT VIEW
(reduced scale)
Guiding — alignment mirror
The cross-section view is drawn through this plane

In the Multiple Mirror Telescope a laser beam from a central guiding-alignment mirror is reflected to larger mirrors clustered around it (see insert). Path lengths are monitored and any changes detected used to bring the mirrors back into proper alignment.



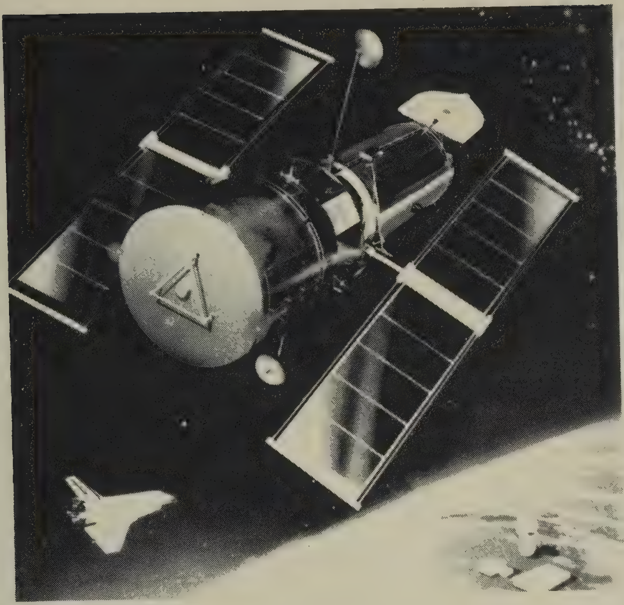
The Multiple Mirror Telescope (MMT) on Mount Hopkins, Arizona, has a cluster of six 1.8 meter diameter reflectors arranged 6-gun fashion. The cluster is carried in an alt-azimuth mounting and the entire observatory building rotates with the telescope.

ror may be monitored and any changes detected used to move the mirrors into proper alignment, providing a continuous dynamic adjustment.

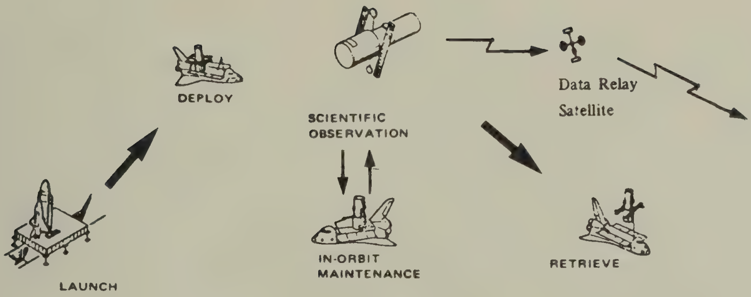
A Multi-Mirror Telescope (MMT) of this design has recently been constructed on Mt. Hopkins, Arizona. Consisting of a cluster of six 1.8 meter mirrors it provides the same aperture area as a single 4.4 meter mirror. A seventh mirror for guiding and alignment is situated at the center of the cluster.

Space Optical Telescopes

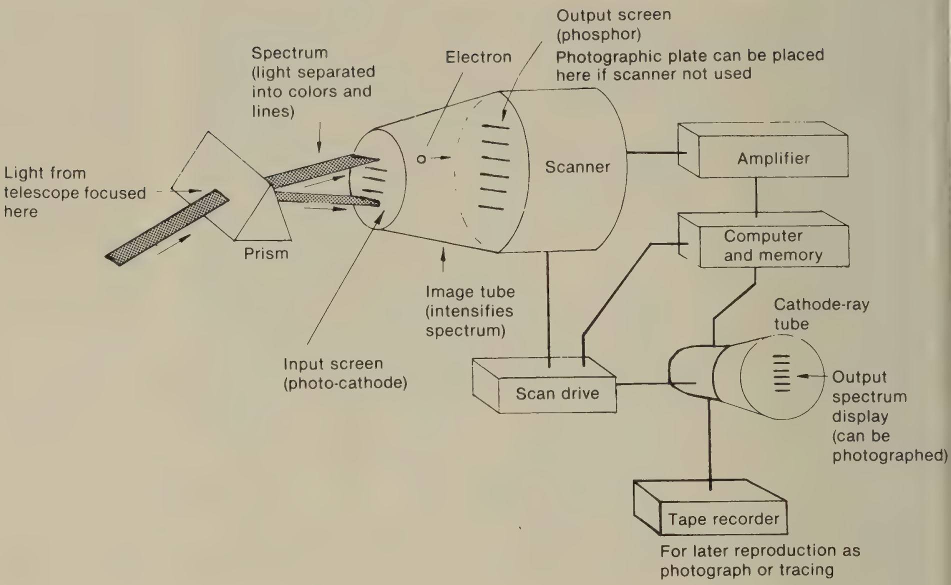
To reduce the absorption, image instability and distortion produced by the earth's atmosphere, large optical telescopes are usually situated on mountains above as much atmosphere as possible. The ultimate improvement is to place a telescope in space completely above the atmosphere. In space the telescope performance is no longer limited by the earth's atmosphere but rather by the optics of the telescope itself. In space, stars appear sharp and steady, the sky is dark and there is no atmospheric absorption.



The Space Optical Telescope. (Courtesy of NASA)



Operational phases of the Space Optical Telescope. Carried aloft by the Space Shuttle it will be released into orbit along with a tracking and data radio relay satellite. Later in-orbit maintenance can be performed or the telescope can be retrieved and brought to earth for refurbishing.


Output screen
(phosphor)
Photographic plate can be placed here if scanner not used
Spectrum (light separated into colors and lines)
Electron
Light from telescope focused here
Prism
Scanner
Amplifier
Computer and memory
Image tube (intensifies spectrum)
Input screen (photo-cathode)
Cathode-ray tube
Scan drive
Output spectrum display (can be photographed)
Tape recorder
For later reproduction as photograph or tracing

Electronic system for intensifying and processing a spectrum uses an *image tube, scanner, amplifier* and *computer.* The spectrum appears on a cathode-ray tube screen as the star is being observed. When a satisfactory display is achieved it can then be recorded on magnetic tape. In the image tube electrons ejected by the photocathode are accelerated and focused by electric and magnetic fields. These electrons in turn produce an intensified image on the output screen or phosphor. Several image tubes may be operated in series for increased intensification.

A number of telescopes have been placed in satellite orbit but the primary motivation for many of them has been to make observations in the x-ray, ultra-violet and other parts of the spectrum where ground-based observations are difficult or impossible due to atmospheric absorption.

The National Aeronautics and Space Administration (NASA) is preparing a SpaceOpticalTelescope for orbiting in the early 1980s. This telescope has several advantages over previous orbiting optical telescopes. It will be larger and can be maintained and repaired while in orbit by an astronaut. It will be launched by the NASA Space Shuttle and if necesary can be retrieved from orbit by the Space Shuttle and returned to earth for refurbishment. Although smaller than the largest earthbound telescopes, the observing conditions in space are so vastly superior to those on the earth that it will be possible to obtain photographs in a few seconds of a quality which could not be duplicated with very long exposures using the best earth-based telescopes.

Photographs, in the form of TV pictures, and other data from the Space Telescope will be transmitted to the ground via a tracking and data relay satellite system. Control of the telescope will be through a NASA Missions Operation Center.

Photocells, Image Tubes and Scanners

To determine if a star changes in brightness, its image is compared on photographs taken at different times or the brightness may be measured with a *photocell* placed at the focus of the telescope. Photons falling on the photocell cathode eject electrons producing an electric current which can be amplified and recorded, providing a system of great sensitivity and precision. The ejection of electrons by photons is called the *photoelectric effect,* a phenomenon discovered by Heinrich Hertz in 1887. Light meters for cameras may employ this effect.

An even more sensitive device, called an *image tube,* has found wide application for increasing the sensitivity of telescopes. Photons falling on an input screen (photo-cathode) eject electrons which are accelerated and focused by electric and magnetic fields and impinge on an output screen (phosphor) producing an intensified image of the one on the input screen. Some image tubes have sufficient sensitivity to record a single photon, the ultimate in sensitivity.

Image tubes are especially useful in intensifying the spectrum of a star where the light is spread out by a prism into its various colors. Carswell and Strittmatter used an image tube with photographic plate at the output to enhance the spectrum of the distant quasar OH471 and measure its high redshift.

An even more sensitive and flexible arrangement for obtaining spectra of faint stars, quasars and galaxies employs a *scanner* which detects the photons emitted by the output screen of an image tube, amplifies the impulses, counts them and presents the resulting information on a cathode-ray-tube screen. While the celestial object is under observation, the display on the cathode-ray-tube-screen becomes clearer and more distinct the longer the observations continue. When a satisfactory display has been attained the observer can elect to record the results on magnetic tape for later study and processing. The great advantage of this system is that the observer can monitor the observations as they are progressing and can either continue or terminate them. When spectra are recorded directly from a prism or via an image tube onto a photographic plate the observer does not know until sometime after the observations are over, the photographic plate developed and inspected, whether the observations were satisfactory. If they were not it may be too late to try again.

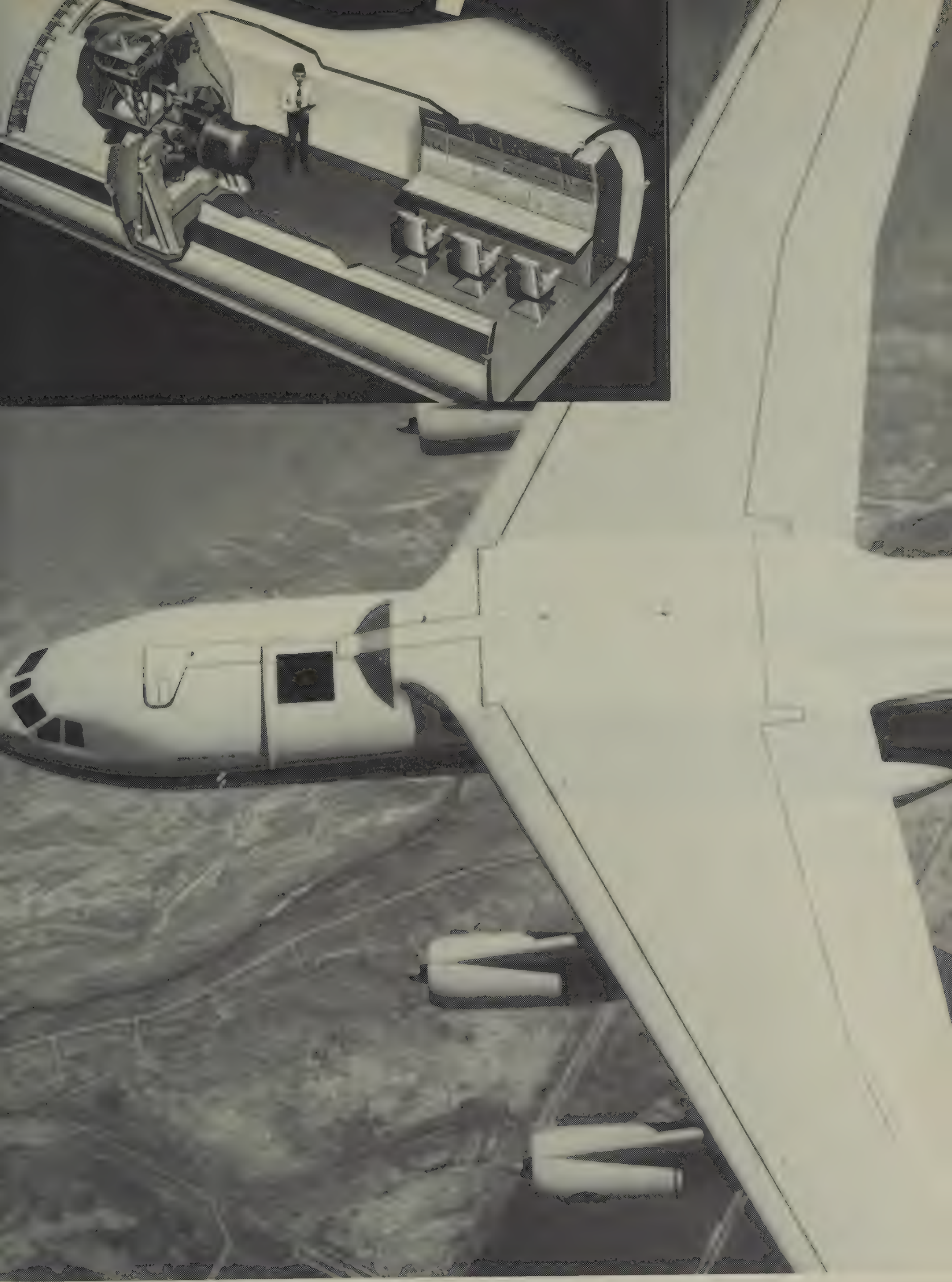
Image tubes and other electronic devices have produced large increases in telescope sensitivity. Concurrent improvements in photographic emulsions and increased sensitivity through hypersensitization have also made direct astronomical photography more efficient and, teamed with the electronic devices, the specially processed new emulsions serve even more effectively as the final recording medium. For example, Alex Smith and Roger Scott at the University of Florida Rosemary Hill Observatory have achieved substantial improvements by a combined nitrogen baking and hydrogen soaking of emulsions prior to their exposure. Smith points out that the photographic emulsion process is in fact a micro-miniature solid-state amplifier capable of a billion-fold gain or enhancement factor. With the proper technique much of its potential can be realized.

Rendezvous with a Star

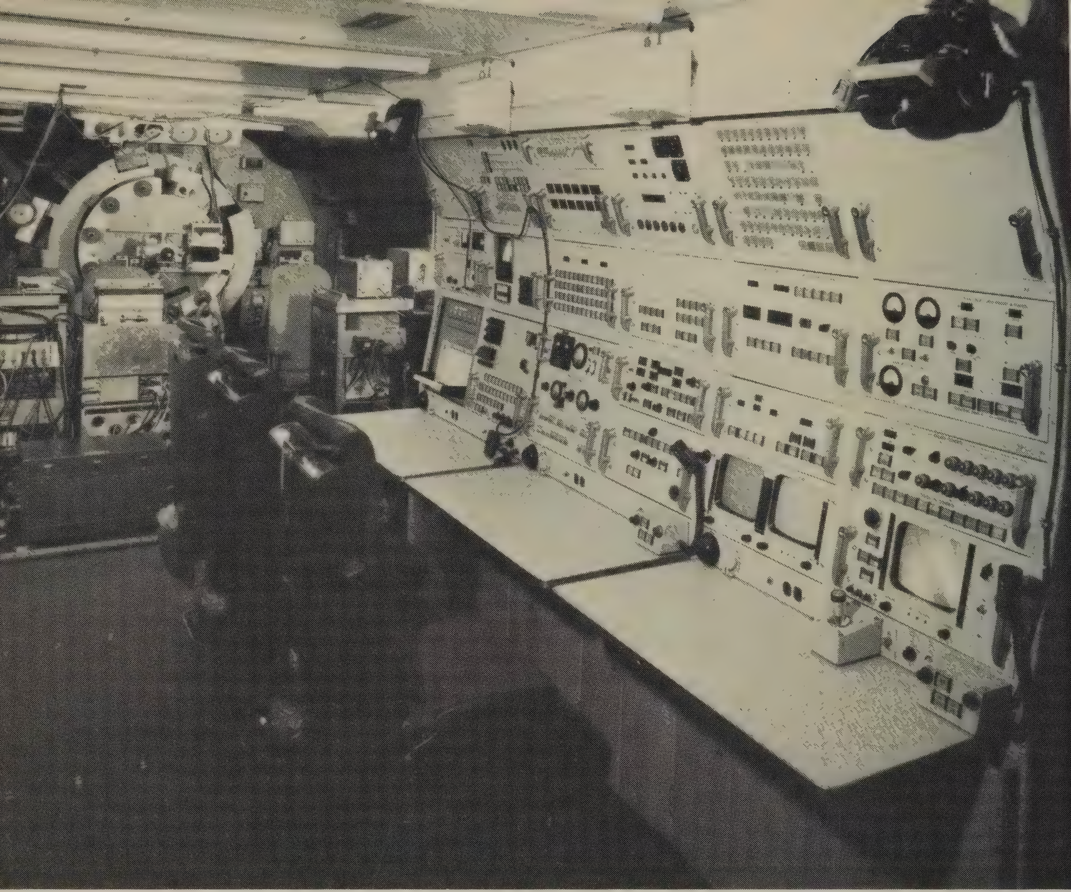
The sun was setting in the west as a big 4-engine jet passed over the South Carolina coast at 12 kilometers altitude. Heading eastward at 800 kilometers per hour, it met the edge of the night racing westward at 1100 kilometers per hour and plunged quickly into the realm of darkness. Taking off from California five hours earlier, the jet was following no regular air route nor traveling to any city or airport. But it did have a mission to fulfill, to rendezvous with a star and a planet.

It was chasing a fleeting point at the end of a line extending through Mars to a distant star, Epsilon Geminorum, as Mars passed in front of or occulted the star. The jet was no ordinary aircraft: it was NASA's Kuiper Airborne Observatory, a huge jet transport plane bursting with astronomical instruments including a 1 meter telescope. It was named for Gerard P. Kuiper, an American astronomer who pioneered in airborne observation. At 12 kilometers altitude it was well above clouds and most of the layers that produce twinkling of starlight so it should be ideal for this occultation observation. It was also above 99 percent of the atmosphere's water vapor, a strong absorber of infra-red radiation. By transporting a sophisticated observatory higher than any mountain, the jet made the atmosphere's optical window more transparent and also widened it into the ultra-violet and infra-red.

On this night, on the eighth of April, 1976, James Elliot, Edward Dunham and Craig Church of Cornell University were aboard with the NASA flight crew of ten to try and record an unusual astronomical event. Mars, on the other side of the sun and about as far in its orbit as it gets from the earth, was only slightly brighter than Episilon "Gem." The sun had just set. Mars and the star hung low in the west and soon would follow the



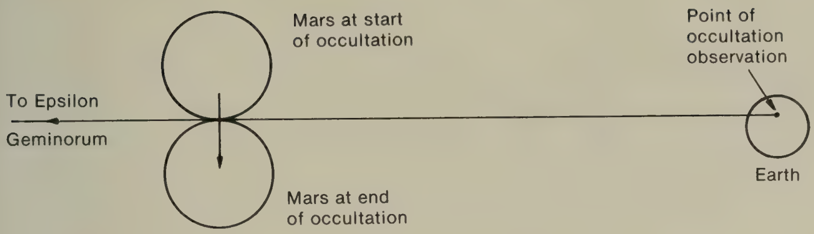
The Kuiper Airborne Observatory in flight with cutaway view (above) of fuselage section with astronomical equipment just aft of pilot's compartment. (Courtesy of NASA)



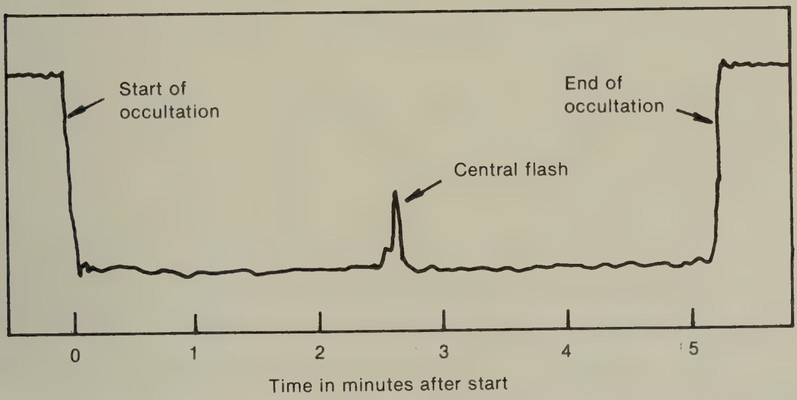
Inside the Kuiper Airborne Observatory looking forward with part of the one meter telescope visible at top left and control consoles at right. (Courtesy of NASA)

sun below the horizon. But before they disappeared Mars would move in front of Epsilon Gem and block it from view for a few minutes. Would it be possible to record this event and even, perhaps, catch that fleeting point and achieve a perfect alignment with Epsilon Gem directly behind Mars?

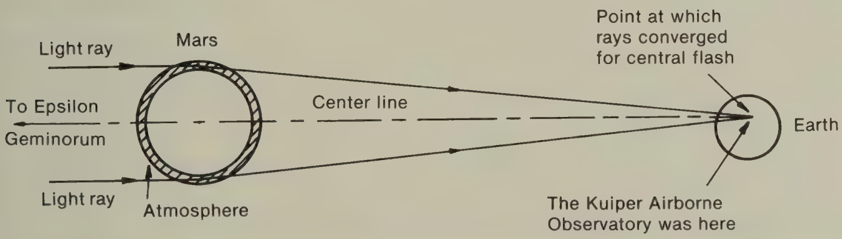
Suddenly the jet began to bank left as the pilot, Ron Gerdes, changed the flight direction to place the jet, now racing north at 800 kilometers per hour, on a collision course with the fleeting Mars-star point speeding east about one hundred times that velocity. Ahead of the wing and just aft of the pilot's cabin a port in the fuselage was opened exposing the 1 meter telescope to the sky. The big mirror was turned to Mars whose light and that of Epsilon Gem would be measured with a photoelectric detector and recorded by a pen on a moving paper chart. The images of the star and planet were also monitored on a TV screen in the control compartment. The NASA fight engineers and Cornell astronomers watched the screen intently as Epsilon Gem and Mars slowly grew closer. Then, as Mars slipped in front



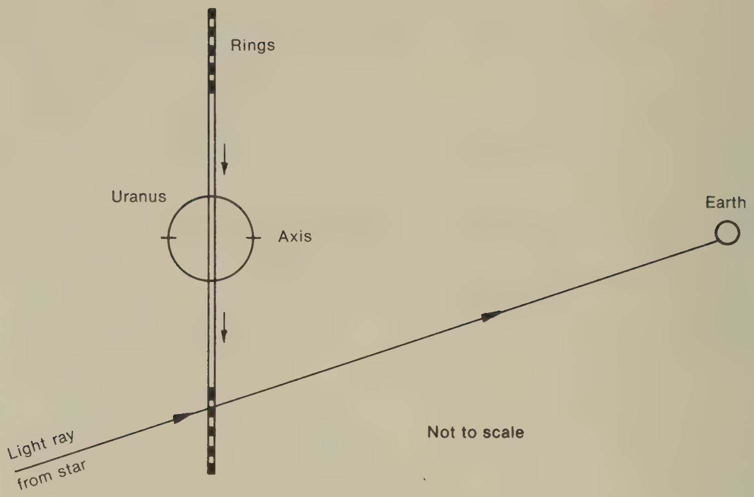
As Mars moved across the line from Epsilon Geminorum, the light from the star was cut off or occulted. Five minutes later Mars had moved enough to uncover the line and end the occultation.



Change in light intensity during occultation showing central flash which occurred at instant of perfect alignment when light from Epsilon Geminorum was bent by Martian atmosphere and focused at a point on the earth as shown below.



of the star, their two images coalesced. Simultaneously the recorder pen dropped abruptly, as the light from the star was cut off, and then drew a nearly smooth level base line. All eyes were now glued to the recorder. Suddenly, after several minutes the pen jumped up abruptly only to fall back again leaving a sharp peak on the record. This peak was puzzling because the occultation was not yet over. The pen continued to draw a nearly straight line for a few more minutes and then quickly rose to the same level



The reason the rings could be observed in the occultation is that Uranus rotates with its axis almost in the plane of the planets, instead of nearly perpendicular to it. Thus, the rings are broadside to our view and acted like the slats of a picket fence as they moved across the light ray from the star.

it had before the occultation started. On the TV screen Epsilon Gem could now be seen emerging from behind Mars. The occultation was over.

But what about the strange peak? A quick measurement showed that it was at exactly the mid-point of the occultation! The astronomers and engineers were charged with excitement: they had observed the *central flash!* It was something no other occultation observers had ever seen. It meant that their alignment with Mars and Epsilon Gem had been perfect, permitting the Martian atmosphere to bend or refract the star light around its edge and bring it into a focus. From this flash and the abruptness of the light change at both ends of the occultation, the astronomers could gain important insights about the extent and uniformity of the Martian atmosphere.

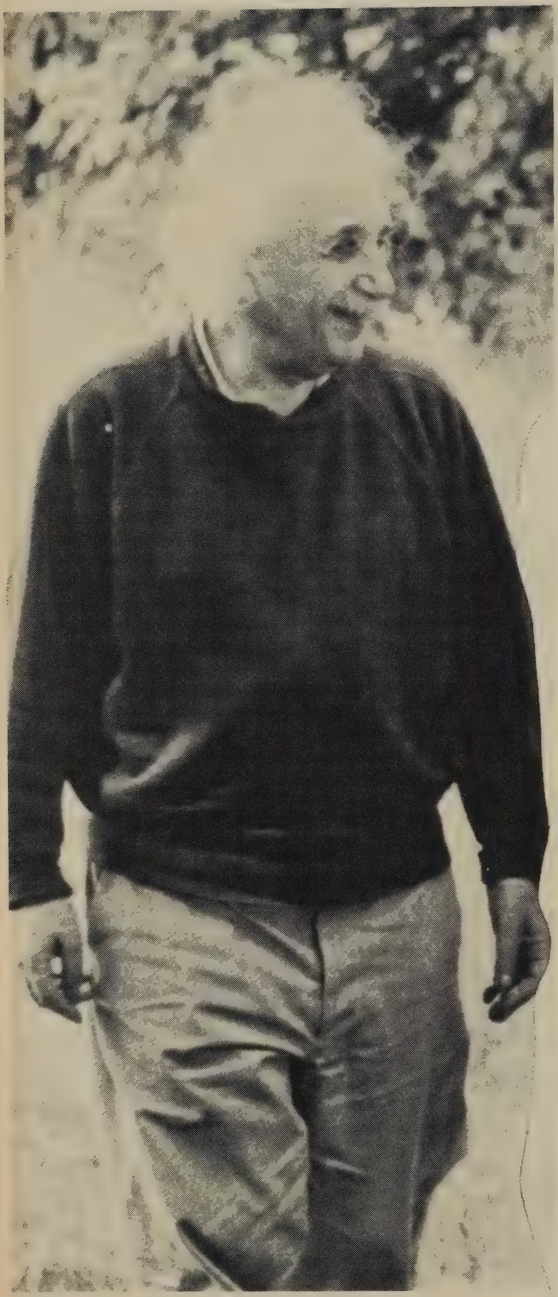
A year after the Mars-Epsilon Geminorum occultation, Ron Gerdes piloted James Elliot on another flight in the Kuiper Airborne Observatory. On this one they flew over the Indian Ocean so that Elliot could observe the occultation of a star by the planet Uranus. Elliot hoped the observations might indicate whether Uranus had an atmosphere but he had a surprise.

About 40 minutes before the star was due to pass behind Uranus, its light was cut off abruptly for seven seconds. Then, in the following nine minutes, it was again cut off four more times. After this the star shone undimmed for the remaining thirty minutes before it was cut off or occulted by Uranus itself. After the star re-emerged there were five more abrupt cut-offs matching the earlier ones. What could have produced these unanticipated extra occultations, five before and five after the main expected one?

It was finally concluded that Uranus, like Saturn, has rings, in fact it has five of them. They had never been seen or photographed but the occultation revealed them. Uranus, discovered by William Herschel in 1781, was now found, almost two centuries later, to have rings like Saturn. Uranus also has five moons or satellites, two of which were discovered by Herschel. Saturn has three rings and nine moons.

The Kuiper Airborne Observatory had been designed to widen the atmosphere's window. In 1975 after eight years of planning, development and testing, NASA commissioned a modified Lockheed C-141 4-engine jet transport plane as the Kuiper Airborne Observatory. Although intended especially for infra-red observations (wavelengths longer than visible), above most of the earth's atmosphere, it also makes possible better observations in the visible and ultra-violet (wavelengths shorter than visible) while providing a highly mobile platform valuable in eclipses and occulatations as demonstrated by the Mars-Epsilon Geminorum and Uranus events. Both of these events were observed in the visible part of the spectrum.

Epislon Geminorum (Epislon Gem for short) is a bright star in the knee of Castor, one of the Gemini twins.



PRINCETON UNIVERSITY

Albert Einstein, patent examiner turned scientist, whose equation $E = mc^2$ relates mass and energy.

His equation implies that a one gram mass (about the weight of an aspirin tablet) is equivalent to 25 million kilowatt-hours of energy. The most direct demonstration of this occurs when matter and anti-matter combine. Thus, if an ordinary aspirin tablet and one made of anti-matter (not yet available) could be brought together, 50 million kilowatt-hours of electromagnetic energy would be released. This is sufficient energy to supply a U.S. city of 5 million all its energy requirements (for heat, light, transportation, etc.) for one hour. (See also page 107).

RADIO ASTRONOMY

Oersted and Faraday

As early as 600 B.C. the Greek astronomer and philosopher Thales knew that amber rubbed with cloth became electrically charged. Also ancient sailors are reported to have used loadstone or magnetic compasses so electric and magnetic effects were known long ago. Still light was regarded as something entirely unrelated to either electricity or magnetism.

The name *electricity,* from the Greek word for amber, was first used about 1600 A.D. by William Gilbert, an English scientist and physician to Queen Elizabeth I, who made important contributions to an understanding of both electricity and magnetism. But it remained for Hans Christian Oersted of Denmark to discover that *electricity and magnetism were related.* In 1819 he was startled to find that an electric current through a north-south wire above a compass caused the compass needle to swing west while reversing the current direction caused the needle to swing east. Oersted had demonstrated unequivocally that an electric current produced a magnetic effect. Twelve years later in 1831 Michael Faraday, in London, demonstrated the reverse effect, namely that magnetism could produce an electric current. The essence of Faraday's experiment can be demonstrated most simply by plunging the end of a long bar magnet through a coil of wire producing a momentary deflection of a current meter indicating the momentary passage of a current. Jerking the magnet out from the coil also produces a momentary deflection but in the opposite direction.

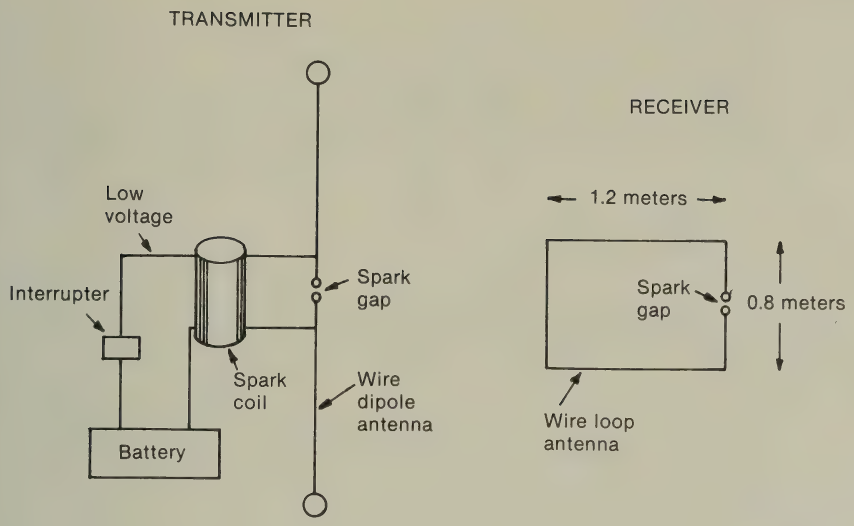
Referring to the region in which electric forces act as *electric fields* and those in which magnetic forces act as *magnetic fields* we can say that Oersted discovered that *an electric current produces a magnetic field* while Faraday discovered that a *changing magnetic field produces an electric current.* The foundation stones had been laid and in 1873 James Clerk Maxwell of Cambridge University, England, published his ''Treatise on Electricity and Magnetism'' in which he presented the first unified theory of electricity and magnetism. He proposed that changing electric and magnetic fields were inter-related and would propagate as a wave phenomenon through empty space at light speed. He concluded that light was an electromagnetic wave, and also that electromagnetic waves of other wavelengths should be possible.

Heinrich Hertz and the First Radio Transmitter and Receiver

In 1888, fifteen years after Maxwell published his book, Heinrich Hertz, a physics professor at Karlsruhe, Germany, produced and measured the first radio waves. He generated them by connecting a spark coil across a gap in a wire 3 meters long stretched between two metal balls. When the coil was connected through a vibrating contactor or interrupter to a battery, sparks jumped the gap. But most significantly, *sparks also jumped a gap in an isolated rectangular loop of wire nearby.* This loop acted as the receiver.

Electromagnetic waves, as predicted by Maxwell, conveyed energy from the straight 3-meter wire through the intervening space to the loop. With his spark transmitter and spark gap receiver, Hertz demonstrated that radio waves could be produced and by this and other experiments established their oneness with light as electromagnetic waves. The length of the waves Hertz generated was about 5 meters, corresponding to wavelengths now used in television broadcasting. The straight wire with gap is often referred to as a *Hertzian dipole or half-wavelength antenna,* since its length is about one-half wavelength.

Heinrich Hertz, inventor of radio.



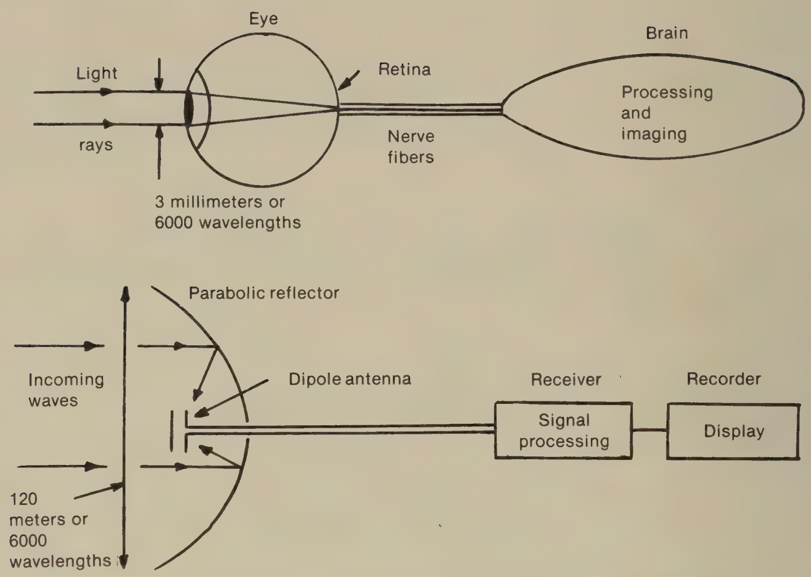
The first radio transmitter and receiver. Spark-generated waves were radiated from a wire dipole antenna 3 meters long. The receiver was a wire loop with a spark gap.

Antennas

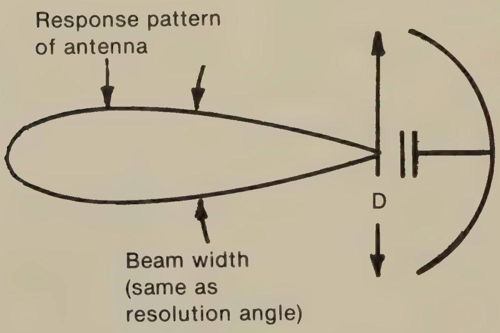
A radio telescope consists basically of an antenna and a receiver with some kind of recorder connected to display the output as a function of time. The antenna captures or collects the radio waves and converts them into impulses which travel along an electrical cable to a receiver. The antenna and receiver-recorder is analogous to the eye-brain combination in which light rays focused on the retina produce impulses that travel along nerve fibers to the brain. However, radio waves are so long that, typically, the antenna may be less than a wavelength long whereas the pupil of the eye is some 6000 wavelengths in diameter. To make radio antennas large in terms of the wavelength they must be very large physically.

One of the simplest antennas is a Hertzian or *half-wave dipole*, devised by Heinrich Hertz during his epic experiments. It consists of a straight wire one-half wavelength long with terminals at its center which connect to a receiver. Maximum response is from a direction perpendicular to the wire with minimum response (effectively zero) in the direction of the ends.

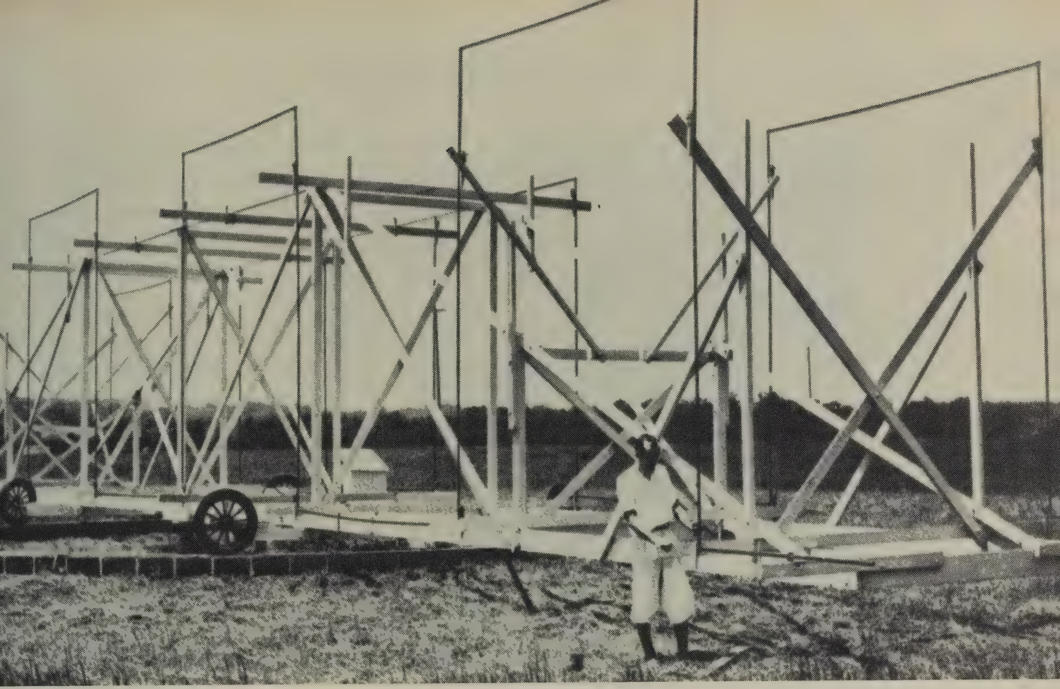
By placing a dipole antenna at the focus of a parabolic reflector, waves can be received from the entire area of the parabola making for higher sensitivity and resolution than possible with a single dipole.



The antenna and receiver-recorder of a radio telescope do for radio waves what the eye-brain combination does for light. But for a radio antenna to have the same aperture diameter in wavelengths (and the same resolution) as the eye, the antenna diameter must be more than 100 meters (for 2 centimeter waves). This can be achieved with a parabolic reflector which collects the waves and focuses them on the dipole antenna connected to the receiver.


Response pattern of antenna
D
Beam width (same as resolution angle)

Response pattern or beam of a radio telescope antenna. The larger the diameter *D* of the dish the narrower the beamwidth.



Karl Jansky and the first radio telescope with which he discovered radio waves from beyond the solar system in 1931, one hundred years after Faraday's experiment. (Courtesy Bell Laboratories).

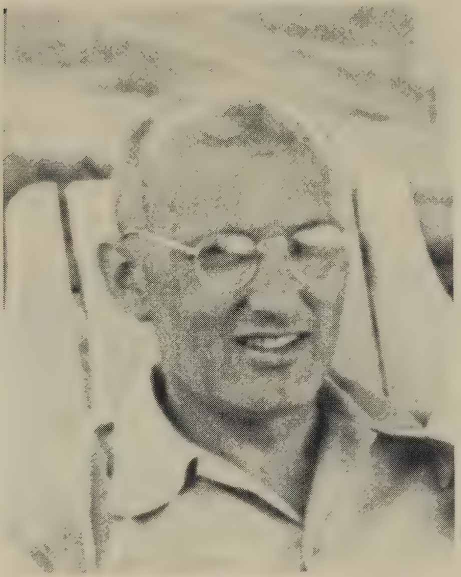
The First Radio Telescopes

A bizarre contraption, reminiscent of the wing frame of an early Wright brothers biplane, rotated slowly on the flat, open expanse of a fallow southern New Jersey potato field. The metal tubes and wooden slats of the 30-meter long ''wing'' rolled on four Model-T Ford wheels round and round completing three revolutions per hour on a circular track 10 meters in diameter.

Nearby in a small wooden shack on a warm sunny afternoon of mid-June, 1931 a slender, young radio engineer, fresh out of college on his very first job, puzzled over a long strip of paper coming from a recorder. The ''wing'' was a radio antenna. Connected to a radio receiver in the shack, the received signals were continuously recorded by pen on the paper strip.

An airplane ''wing'' rotating on automobile wheels in a potato field — what an improbable, unlikely combination! Yet it had been constructed for a definite purpose. The young engineer, Karl Jansky, had built it to investigate the direction of arrival of the crackling thunderstorm noise or ''static'' which interfered with the telephone conversations on the trans-Atlantic short-wave links of the Bell system.

Jansky found what he was looking for. Some static came from local thunderstorms, other static from more distant ones, the strength fluc-



Karl Jansky, who opened a new window on the universe.

tuating greatly from day to day. But also, so weak that he might have ignored it, was a faint persistent static, always there, whose direction moved almost completely around the horizon once each day. Listening to the static with earphones Jansky described it as a hissing sound "that can hardly be distinguished from the receiver noise." This hiss-like static Jansky had not expected or anticipated but it excited his curiosity and he determined to track it down.

He ruled out local interference from power lines or electrical equipment; he ruled out terrestrial sources. Could it come from the sun? After further observations he concluded that the noise was coming from beyond the earth, beyond the sun and solar system.

Jansky's airplane "wing" was the first radio telescope and with it he opened a new corridor to the cosmos! A universe full of radio sounds to which man had been deaf since time immemorial now suddenly burst forth in full chorus upon him. Humans could now turn, not only their eyes, but also their radio ears to the heavens!

Jansky's discovery is now recognized as epoch-making but at the time astronomers and engineers hardly raised an eyebrow. It was a truly historic occasion when Jansky presented the final paper about his discovery at a national convention of the Institute of Radio Engineers at Detroit, Michigan, in July, 1935. However, scarcely two dozen people were in the audience. The author of this book was fortunate to be one of them.

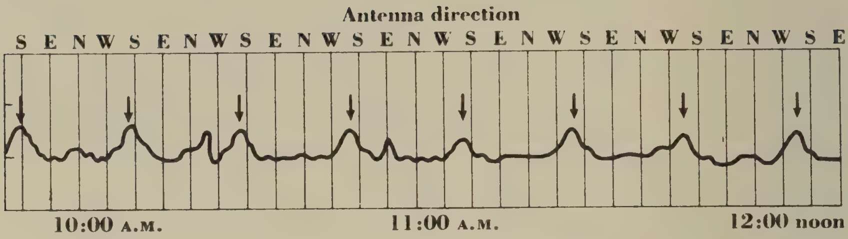
Jansky was soon transferred to other work and years passed before the importance of his discovery was generally realized. Then, radio astronomers found that space was full of radio waves emanating from innumerable celestial "broadcasting stations" so powerful that they made the strongest ones on earth seem utterly insignificant. And they transmitted at all wavelengths, broadcasting a kaleidoscopic Babel of radio sounds that would be a challenge to astronomers to interpret. Jansky's epic discovery was one of serendipity; he had not been seeking extraterrestrial radio signals but he had discovered them.

In 1895 Oliver Lodge wondered if the newly discovered Hertzian waves, we now call radio waves, might not be emitted by the sun. He set up a simple receiving system in Liverpool, England, but detected nothing except static and disturbances he attributed to passing street cars and nearby electrical equipment. Lodge concluded correctly that if such waves did exist his equipment was not sensitive enough to detect them. He further recommended that subsequent experiments be conducted "in some isolated country place" to avoid man-made electrical interference. Lodge was a man ahead of his time.

In 1895 Guglielmo Marconi of Italy began experiments looking toward the use of radio waves for communication purposes culminating in his dramatic transmission of radio signals across the Atlantic ocean in 1901.

During the following years wireless or radio communication became more commonplace and in 1920 radio broadcasting began. The wavelengths used were generally quite long, 100 meters or more. During the 1920s with the advent of vacuum tubes to replace spark gaps, radio amateurs and others found that wavelengths as short as 10 meters were useful for communication over intercontinental distances. Transoceanic telephone conversations became practical but the static associated with lightning discharges was sometimes strong enough to garble the speech. So it was in 1930 at the Bell Telephone Laboratories that Karl Jansky was assigned the problem of investigating the direction of the arrival of static which interfered with the short-wave trans-Atlantic radio links of the Bell system.

To study this problem a directional or beam antenna was needed, that is, one that has a greater response in a certain direction than in others, and it also needed to be steerable, that is mounted so that it could be pointed in different directions. Accordingly, Jansky built an array of dipole antennas 30-meters long and mounted it on rubber-tired automobile wheels rolling on a circular track and as just related he found a puzzling hiss or "interference." After a year's observations he noted, by comparing records of succeeding days, that the source of the "interfering static" did not reoccur in exactly 24 hours but in about 4 minutes less. This is the time the earth rotates with respect to the stars and it could mean only one thing: the so called "interference" was coming from beyond the earth and beyond the

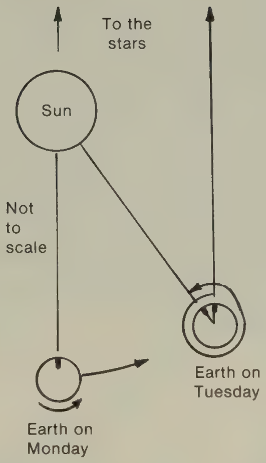


The faint hiss-like static made little bumps at 20-minute intervals on Jansky's record whenever his antenna beam was pointed toward the center of our galaxy. Note that the direction of the bumps shifts from the south (S) to southwest in about two hours.

sun. Further observations by Jansky indicated that the signals were strongest when his antenna was pointed toward the constellation Sagittarius, in the direction of the center of our Milky Way system or galaxy.

In 1937 another radio engineer, Grote Reber, of Wheaton, Illinois, built a 9-meter diameter parabolic reflector antenna in the backyard of his home. Reber was an avid radio amateur who had communicated with other amateurs all around the world and to expand his horizons wondered if he could bounce a radio signal off the moon and receive the echo. Calculations convinced him that his transmitting and receiving equipment were inadequate. However, he had heard of Jansky's work and decided to find if he too could detect the "cosmic static."

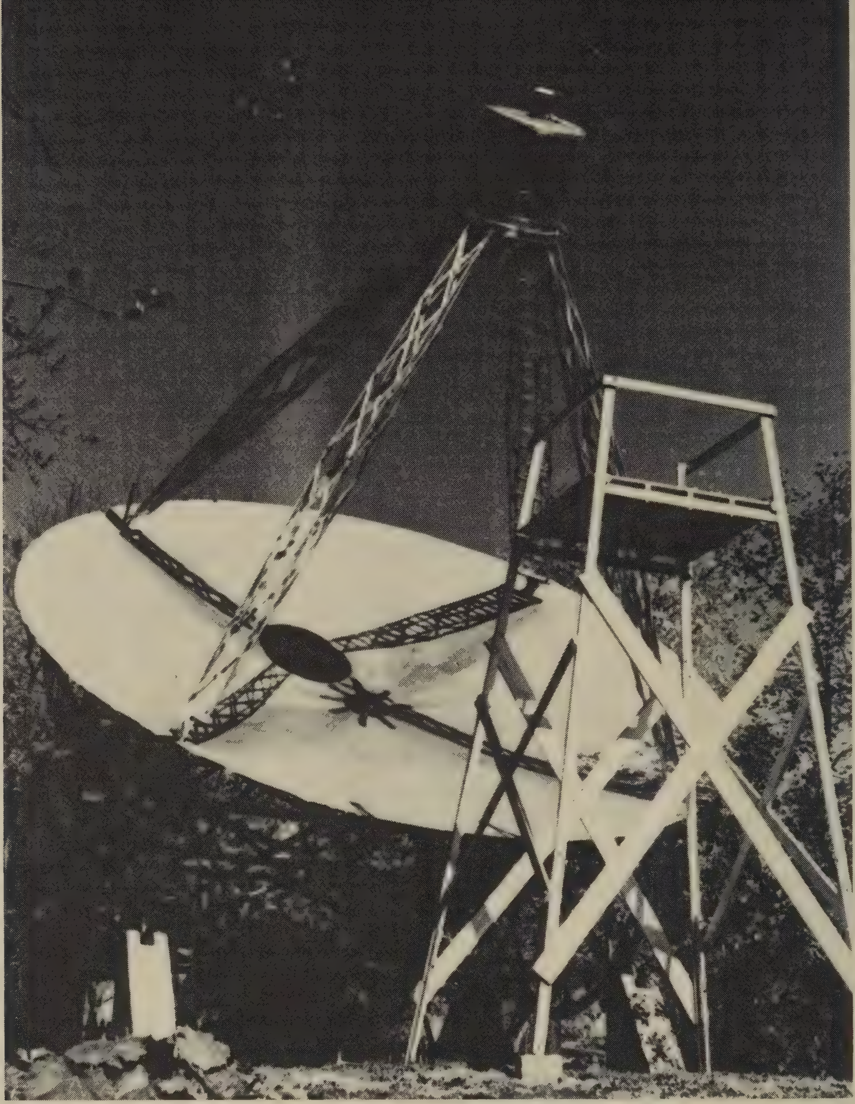
Jansky made his observations at about 15 meters wavelength. The most logical assumption at the time was that Jansky's static would obey Planck's radiation law and be stronger at shorter wavelengths so Reber made his first attempt at 9 centimeters wavelength. He detected nothing. He modified his receiver to work at the longer wavelength of 33 centimeters. Still nothing. Again he rebuilt his receiver making it work at the yet longer wavelength of nearly 2 meters. This time, in the spring of 1939, Reber was successful in detecting the cosmic static and found that it was strongest toward Sagittarius, in the direction of the center of our galaxy, as Jansky had reported. Although Reber's antenna was smaller physically than Jansky's, his wavelength was much shorter so his antenna was actually larger in terms of wavelengths and, therefore, it had a narrower response pattern or beam and it could observe finer detail in the radiation from the sky.



The earth turns once per "star day" but slightly more than once per "regular" (or civil) day. "Star time" is what astronomers call sidereal time. One *sidereal* or star day is the time required for the earth to make one revolution with respect to the stars. A regular (or civil day) is the time required for the earth to make one revolution with respect to the sun. One star day is about four minutes shorter than a civil day.

Jansky's antenna rotated horizontally (or in azimuth). Reber's antenna rotated in elevation or declination. By setting his parabolic dish antenna at a given declination and then letting the earth's rotation sweep the beam west to east across the sky (in right ascension), Reber could observe a full band or zone around the sky each day. Tilting his dish to adjacent declinations on successive days, Reber was able to survey the whole sky observable from Wheaton and he produced the first maps of the radio sky. In addition to radiation from our galaxy, he found "hot spots" or discrete regions of radiation in Cygnus, Cassiopeia, Canis Major and Puppis.

Grote Reber, who made the first maps of the radio sky.

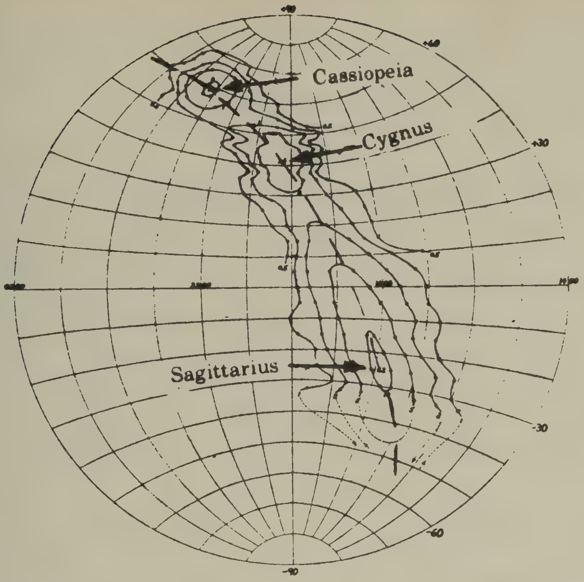


Parabolic reflector radio telescope with which Grote Reber made the first maps of the radio sky in 1939. The parabola could be tilted in declination (up and down). The earth's rotation provided motion in the perpendicular direction (right ascension).

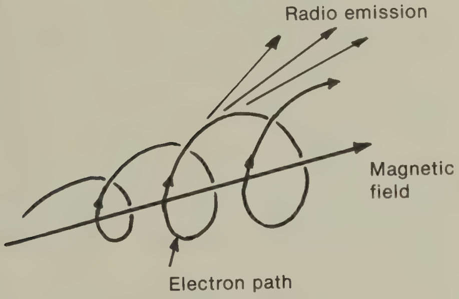
Reber's antenna may be considered to be the prototype of the modern radio telescope.

Reber's dish (9 meters diameter) operated at 1.87 meters wavelength. This made it 4.8 wavelengths across. Dividing 60° by 4.8 gives 12.5° as the beam width or resolution of Reber's telescope.

By contrast, Jansky's antenna (30 meters long) operated at 15 meters wavelength so it was only 2 wavelengths long. Dividing 60° by 2 gives 30° as the beam width of Jansky's antenna.



The first radio map of the sky. Made by Grote Reber in 1944, it shows radio emission along the plane of the Milky Way or galaxy (dashed line). There is a large maximum (11 units) in Sagittarius (the galactic center), and smaller maxima in Cygnus (3 units) and Cassiopeia (2 units). Measured at 2 meters wavelength.



The radiation Jansky and Reber detected has been identified with very fast electrons spiraling in interstellar magnetic fields. Man-made particle accelerators, called synchrotrons, produce radiation in a similar way: hence, the radiation is referred to as *synchrotron radiation.*

The Song of Hydrogen

Reber published some of his early results in 1940. A copy of Reber's article reached Nazi occupied Holland during World War II. Young Hendrick van de Hulst of the Leiden Observatory was interested. It seemed probable from Reber's observations on 2 meters wavelength and Jansky's on 15 meters that the cosmic static was a continuum radiation, that is, one which extended continuously over a wide range of wavelengths.

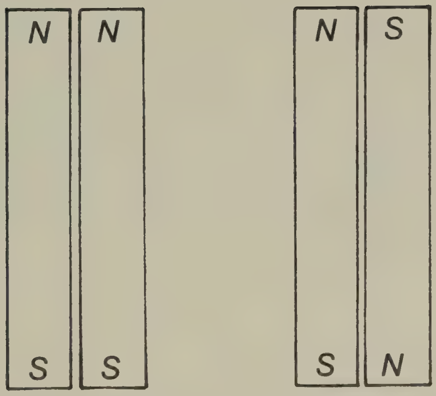
The optical counterpart of this continuum radiation is white light, which is a blending of all colors. Sharply defined colors are produced by a narrow band of wavelengths called a line, as for example, the yellow lines of sodium and bluish ones of mercury. It was in this context that van de Hulst wondered if, in addition to the radio continuum radiation, there might possibly be some radio lines. He investigated and in 1944 reported that the hydrogen gas of interstellar space was a likely source. Each atom of hydrogen might be expected to emit a beep of 21 centimeters wavelength radio radiation during an internal transition (electron spin flip) once in a long while, measured in millions of years, but there was suspected to be so much hydrogen throughout space that van de Hulst thought that the combined effect of all these beeps might possibly be observable.

Van de Hulst was right. Seven years later Harold Ewen and Edward Purcell at Harvard University detected the 21 centimeter "song of hydrogen" coming from Sagittarius in the direction of the center of our galaxy, the same place Jansky and Reber had earlier found to have a maximum of radio emission. The difference was that the song of hydrogen was emitted at a single wavelength while Jansky's and Reber's static was synchrotron radiation emitted at many wavelengths. The *line emission* comes from an electron belonging to a hydrogen atom. It is a captured, orbiting, spinning electron which can flip. The *synchrotron radiation* comes from free, fast-moving electrons spiraling in the magnetic fields of space.

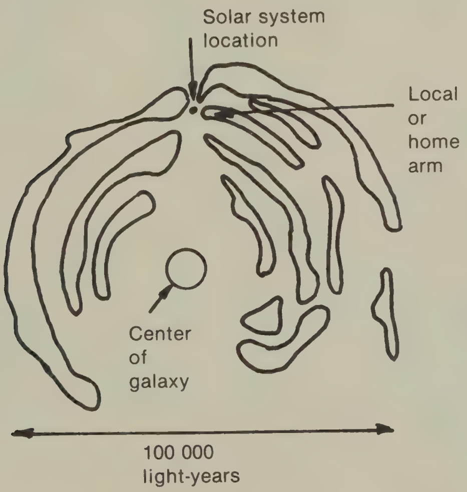
The song of hydrogen is like the plaintive, single note of a flutist performing beside a great waterfall. Jansky and Reber heard the waterfall; Ewen and Purcell heard the flutist.

We are situated inside a spiral arm and because of absorption of light by the gas and dust it is not possible to see very far in the galactic plane and note the spiral structure by optical means. However, it is obvious to even our unaided eye that the portion of the galaxy we can see is highly flattened.

Subsequent observations of the hydrogen 21 centimeter emission from the sky have resulted in the first maps showing the spiral structure of our galaxy because the hydrogen tends to be more abundant along the spiral arms. The accompanying hydrogen map of our galaxy was constructed from Dutch and Australian observations by radio astronomers Gart Westerhout and Frank Kerr.



The 21 centimeter photon emitted during the flip in the electron-spin of a hydrogen atom is analogous to the release of energy when one of a pair of bar magnets flips over, the configuration changing from that at the left (like poles together) to the lower energy state at the right (unlike poles together). (N = north pole, S = south pole; unlike poles attract, like poles repel).



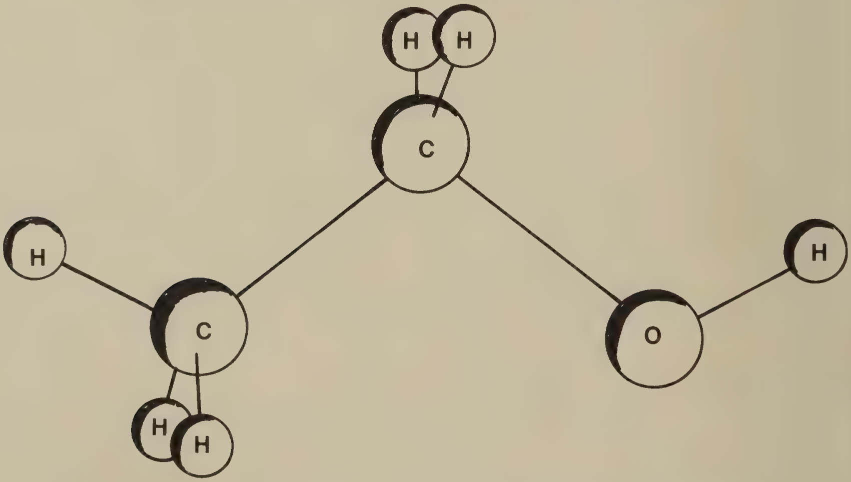
Distribution of hydrogen in our galaxy as detected by the 21 centimeter radiation showing part of the spiral arm structure (after Frank Kerr and Gart Westerhout). Compare this broadside view with the sketch of our galaxy (page 17) and the photograph of the Whirlpool galaxy (M51) (page 23).

Although any line of sight in the galactic plane passes through several spiral arms it is possible to distinguish between the hydrogen radio emission from the different arms because the galaxy is rotating and different locations have different relative velocities with respect to us. This means that the hydrogen emission is shifted to wavelengths somewhat longer or shorter than 21 centimeters depending on whether the location is receding or approaching. For given assumed rotational velocities the locations of the spiral arms can be traced and it is apparent that our Milky Way system is a spiral galaxy similar to M81, M51, or M31.

A Cosmic Cocktail

Since the discovery of the hydrogen line, other lines have been detected with radio telescopes produced by water, ammonia, acetylene, formaldehyde, sulphur dioxide, ethyl alcohol and other compounds. Sufficient ethyl alcohol to make trillions upon trillions of fifths at 200 proof has been found in a single interstellar cloud, more than enough for a cosmic cocktail of gargantuan proportions. The discovery of so many different molecular forms in copius amounts in the cold void of almost empty space was quite unexpected.

ALCOHOL FOR A COSMIC COCKTAIL



The ethyl alcohol molecule (CH_3CH_2OH). The atoms marked C are carbon, those marked H are hydrogen and the one marked O is oxygen. Vibrations of the molecule send out 3.5 millimeter radio waves. Vast amounts of ethyl alcohol have been found in interstellar space. Even if there is no life in space, there is at least one of the amenities of the good life in abundance.

SOME MOLECULES FOUND IN SPACE

Name	Chemical formula
Ammonia	NH_3
Water	H_2O
Hydrogen sulfide	H_2S
Carbon monoxide	CO
Hydrogen cyanide	HCN
Formaldehyde	H_2CO
Formic acid	$HCOOH$
Cyanoacetylene	HC_3N
Methyl alcohol	CH_3OH
Methylcyanide	CH_3CN
Ethyl alcohol	CH_3CH_2OH
Hydroxyl radical	OH

The bulk of the material in many large clouds in interstellar space consists of these molecules. The line radiation from most of the molecules is at millimeter wavelengths.

Jamming by the Sun

Another important discovery came during World War II. In February, 1942, British anti-aircraft gun-control radars operating along the English channel suddenly experienced severe interference or jamming rendering them useless. The military commanders feared that the Germans had constructed a new kind of jamming system across the channel and that a large-scale air attack on England was imminent. Dr. J.S. Hey, a British scientist, was called in to investigate and concluded that the "jamming" was not by the Germans by rather from the sun which had some large active spots on its disc at the time. The waves Oliver Lodge had sought from the sun in 1895 had at long last been observed. If Sir Oliver had lived but two more years, until 1942, he would have known that he had been on the right track.

The February, 1942, event marked the first detection of a radio outburst from a celestial object and, after the war, helped generate a new active interest in radio astronomy. Galileo reported spots on the sun in 1611. Now three centuries later, sun spots (or regions close to them) were found to emit radio waves.

Cygnus A — An Exploded Galaxy

Following World War II radio astronomers built radio telescopes in England, Australia and Holland, extending Reber's work. A number of isolated sources of radio emission were located. One in the constellation of Cassiopeia called Cassiopeia A or Cas A for short and another in Cygnus

MOUNT WILSON OBSERVATORY

Walter Baade of Palomar, who first photographed the distant Cygnus A galaxy. Baade is also known for his classification of stars into two "populations": *Population I,* the bright, young stars associated with the gas and dust of the spiral arms, and *Population II,* the older stars found in the galactic halo and nucleus.

designated Cygnus A were a great mystery because, although very intense, there seemed to be no unusual optical objects at their locations in the sky. It was obvious that radio astronomy was revealing a new class of objects in a radio sky which bore little resemblence to its optical counterpart.

More accurate radio positions were needed to narrow the optical search and in 1951 Graham Smith obtained a much more accurate position for Cygnus A with a new radio telescope he and Martin Ryle had built at Cambridge University, England.

On August 22, 1951, Smith air-mailed the position to Walter Baade of the Mt. Palomar Observatory, California. On his next observing session on Palomar Mountain with the big 5-meter telescope on September 4th and 5th, Baade took long exposure photographs in blue and yellow light and noted the tiny, faint smudge of a strange-appearing very distant galaxy which coincided with Smith's position.

From its small size, Baade estimated that the galaxy was at a distance of at least several hundred million light-years. More recent estimates, based on the 6 percent redshift of its optical spectrum, (see page 183), put its distance at nearly one billion light years. Here was a radio source, one of the very strongest in the whole sky, which was far, far beyond our galaxy!

If such a strong radio source corresponded to this faint optical galaxy, it suggested that other weaker radio sources might correspond to even more distant objects and that radio astronomy might play a very important role in probing our universe to its ultimate depths. Time has shown this to be indeed true.

Subsequent to Baade's identification, the radio emission from Cygnus A was found to be actually coming, not from the faint optical galaxy itself, but rather from a double source consisting of two separate regions with the galaxy half-way between. The position Graham Smith had measured at Cambridge was like the "center-of-gravity" of the double radio source which happened to fall close to the galaxy because the two halves of the double source are quite symmetrical.

Cygnus A was the first of a number of radio sources found to be double with an optical galaxy situated between. It is thought that the radio emission is due to *synchrotron radiation* originating from regions containing high velocity electrons moving in magnetic fields with both electrons and fields having been ejected in a titanic explosion from the nucleus of the galaxy at an earlier time. The galaxy produces little radio radiation while the electron clouds produce little or no optical emission.

In synchrotron radiation (so named for synchrotron accelerators on the earth which produce radiation of this type) a charged particle such as an electron moving perpendicular to a magnetic field at nearly the speed of light describes a circular path and emits a beam or cone of radiation in the forward direction. Furthermore, the beam is linearly polarized in the plane of the circle.

If the electron motion is not quite perpendicular to the magnetic field the electron will describe a spiral path but if its velocity is sufficiently high it will still emit synchrotron radiation in its forward direction.

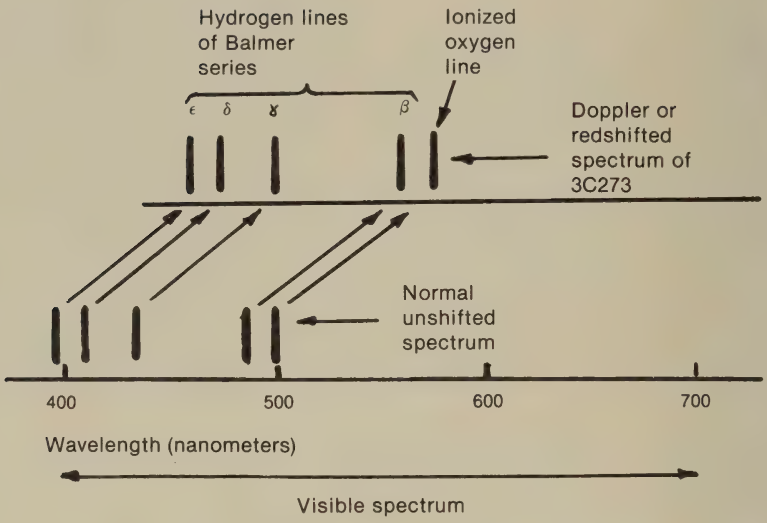
Most radio sources are believed to emit by the synchrotron process because many radio sources tend to exhibit some linear polarization and their radiation tends to become stronger at longer wavelengths, both in accord with what might be expected for synchrotron radiation. The increasing strength with increasing wavelength is just the opposite to that of *thermal radiation* and explains why Reber was not able to repeat Jansky's observations at too short a wavelength. To distinguish the synchrotron radiation from the thermal type it is called *non-thermal* radiation.

Galaxies like M31 with relatively weak radio emission and objects like Cygnus A with very strong radio emission led to the division of galaxies into two classes: so-called *normal galaxies* like M31 and so-called *radio galaxies* like Cygnus A.

Some radio sources do exhibit a thermal spectrum. The radio radiation from the moon is of this type and the sun has a thermal spectrum at centimeter wavelengths or less. Also an ionized gas cloud may emit thermal radiation. The Orion nebula is an example. Whereas synchrotron radiation, which is sometimes called *magneto-bremsstrahlung*, requires the presence of a magnetic field, thermal radiation does not.

The First Quasar

The 21-centimeter hydrogen line was detected by Ewen and Purcell in 1951, the same year Baade photographed the Cygnus A galaxy. Over the next years more radio sources were located and many of these were iden-


Hydrogen lines of Balmer series
Ionized oxygen line
ε
δ
γ
β
Doppler or redshifted spectrum of 3C273
Normal unshifted spectrum
400
500
600
700
Wavelength (nanometers)
Visible spectrum

Normal or unshifted lines in the optical spectrum of hydrogen and oxygen (lower) and as observed at longer wavelengths in the optical spectrum of 3C273 (upper) due to 3C273's recessional velocity giving rise to a Doppler or redshift.

tified with optical objects. At the position of radio source 3C273* there was an object which had the appearance of a star rather than a galaxy. However, its optical spectrum was not the same as for a star. It was described as a *quasi*-stell*ar* object, or more concisely as a *quasar*, an object which looked like a star but wasn't one.

In 1963 Maarten Schmidt and Jesse Greenstein of the Mount Palomar Observatory reported that emission lines in the optical spectrum of 3C273 corresponded to some of the hydrogen emission lines of the Balmer series typical of stars if they were doppler or redshifted by the unprecedentedly large amount of about 16 percent.**

This implied that 3C273 was receding at about 16 percent of the velocity of light and that its distance was about two billion light years or more than twice as far as Cygnus A. This was another big jump into the depths of the universe.

In spite of its great distance 3C273 is a relatively strong radio source and also a relatively strong optical object (only about 1/100 the brightness of the faintest stars visible to the unaided eye). This means that 3C273 must be a very powerful object (producing 10^{40} watts). and if it is a galaxy (or aggregation of stars) its starlike appearance means that the power must be coming from a core or nucleus containing many stars but occupying a spherical volume only a few thousand light years in diameter. If our sun were typical of the stars in the nucleus of 3C273 it would take 100 billion (10^{11}) of them to account for 3C273's optical power output and more than a trillion trillion (10^{24}) suns to account for 3C273's radio power output.

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* Source 273 in the 3rd Cambridge University survey.

** For example, the Balmer delta line at 410 nanometers was Doppler shifted to 475 nanometers. The difference divided by 410 nanometers yields a redshift value of 0.159 or nearly 16 percent or a velocity of 16 percent of the velocity of light.

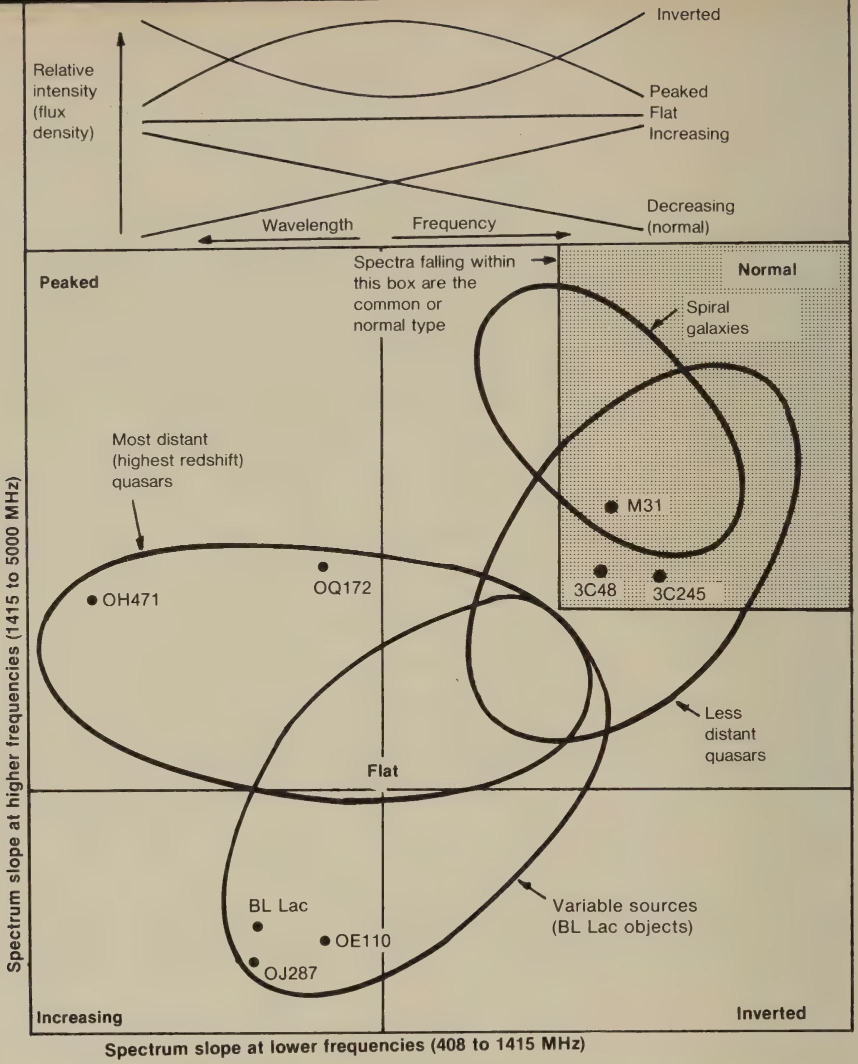
The sun produces most of its power by the conversion of hydrogen into helium (fusion process) with a fraction of the mass converted into energy. According to Einstein's mass-energy equivalence relation $E = mc^2$, where E is the energy (in joules), m the mass (in kilograms) and c equals 300,000 kilometers per second (the velocity of light).

If a star of the mass of the sun (about 10^{30}) kilograms is converted at one percent efficiency (a reasonable assumption) into energy according to Einstein's relation we obtain a power equal to that radiated by 3C273 if such stars are consumed *at the rate of about one per month.* If 3C273's nucleus contains as many as a billion stars, 3C273 could not maintain its present output level for more than 100 million years, a short time for a galaxy. Thus, 3C273 can't last long at its present power level. Our own galaxy is believed to be 10 billion years old and good for many more billions of years.

Following on the heels of 3C273 many other quasars were discovered in the following years with redshifts climbing from 16 percent to many over 100 percent and culminating in quasars with redshifts over 300 percent.

Radio Spectra

Is it possible to determine the redshift and distance of a radio source without first identifying it with an optical object and then measuring the doppler shift of lines in its optical spectrum? In principle this could be done if a line in the radio spectrum, such as the 21 centimeter line of hydrogen, could be found. Although this method has succeeded in a few cases it is, in general, difficult to apply because in a distant galaxy such a line is usually very weak compared to the radiation distributed continuously across the spectrum. Although a redshift can't be determined, a number of things, however, may be learned from the continuous radio spectrum from the way the intensity varies with wavelength.


Relative intensity (flux density)
Inverted
Peaked
Flat
Increasing
Decreasing (normal)
Wavelength
Frequency
Peaked
Spectra falling within this box are the common or normal type
Normal
Spiral galaxies
Most distant (highest redshift) quasars
M31
OQ172
OH471
3C48
3C245
Less distant quasars
Flat
BL Lac
OE110
OJ287
Variable sources (BL Lac objects)
Increasing
Inverted
Spectrum slope at higher frequencies (1415 to 5000 MHz)
Spectrum slope at lower frequencies (408 to 1415 MHz)

The spectra of radio sources may be divided into five extreme or pure types (increasing, decreasing, flat, peaked or inverted) as shown in the top diagram of source strength or flux density versus frequency. In general, sources range from these extreme types through all gradations in between and any particular spectrum places the source at a specific point or location on a shape diagram as shown below. All sources are compared with respect to a central reference wavelength of 21 centimeters.

Using such a diagram, Erich Pacht of the Ohio State University has found that different kinds of objects such as galaxies and quasars tend to cluster in different parts of the diagram as suggested by the elliptical contours. Thus, the radio spectrum alone can often predict what kind of object the radio source is likely to be. For example, the peaked spectrum objects tend to be quasars with large redshifts.

Radio source spectra can be divided into the *normal type* (strength of radiation decreasing with decreasing wavelength) and *centimeter enhanced type* which includes flat, peaked or other shapes not of the normal type. Using a shape diagaram, the radio galaxies tend to cluster in one part of the diagram (normal spectra) while high and low redshift quasars and a special group of variable quasars, called BL Lacertae objects (BL Lac for short), cluster in other parts of the diagram. With such a diagram the radio spectrum of a newly discovered source can provide an immediate clue as to the nature of the source prior to its identification with an optical object and the acquisition of an optical spectrum. The results are especially useful for a class of radio sources that can't be identified with any optical object, photographs with big optical telescopes revealing no object at all at the radio position. These *blank fields,* as they are called, suggest that the radio sources are so distant that the light from them is too faint to be detected. For these objects our knowledge may have to come entirely from the radio observations.

A Matter of Three Degrees

The shiny aluminum structure was as big as a three-story house. Standing on a hill at Holmdel, New Jersey, not far from where Karl Jansky had constructed his rotating antenna three decades before, it looked like a giant sugar scoop. And it was a scoop, but for radio waves rather than sugar. In other words, it was an antenna, then being used for receiving 7 centimeter waves. The scoop had been built for intercontinental radio telephone communication via satellites.

On a spring day in 1965 it became clear that the big scoop had uncovered a problem. When it was turned to parts of the sky devoid of radio sources, the receiver output was larger than expected. Converted into temperature, the excess amounted to three or four degrees.

Any telescope may be regarded as a temperature measuring device. Thus, a photo-electric indicator connected to an optical telescope might be expected to register a very low temperature when the telescope is pointed at the empty dark sky but thousands of degrees when pointed at the sun. In the same way the receiver output of a radio telescope can be used to measure a "temperature" for radio sources or for the apparently empty regions of the sky background between radio sources. At meter wavelengths the sky background temperature may be hundred of degrees celsius above absolute zero* due to synchrotron emission from electrons in our own galaxy but at wavelengths as short as 7 centimeters this becomes very weak, as Reber had found earlier, and the decreasing trend suggested that the sky background temperature at 7 centimeters should be close to zero.

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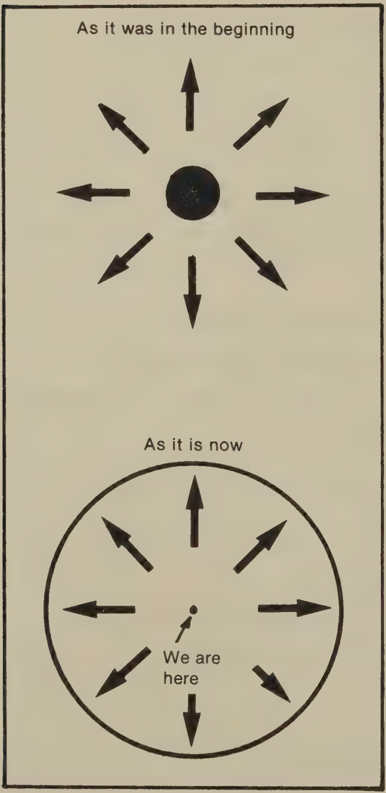
* The temperature in degrees celsius above absolute zero is called the kelvin temperature.

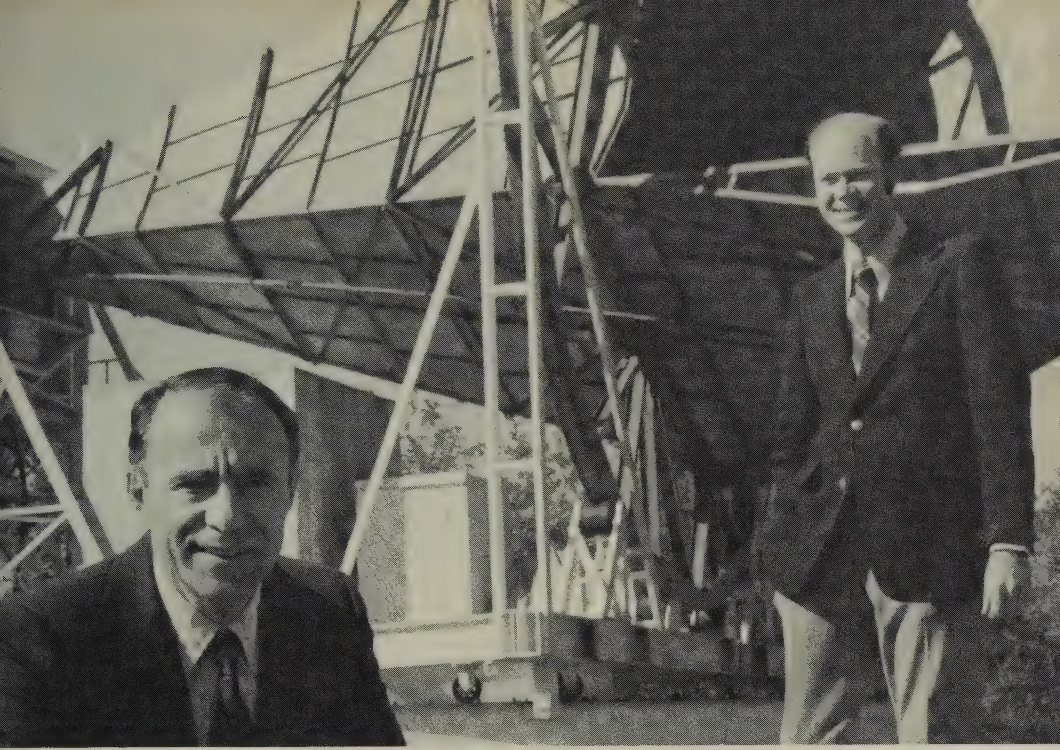
Arno Penzias and Robert Wilson of the Bell Telephone Laboratories were attempting to measure this faint background as part of their study of our galaxy. When they pointed their antenna at a region of the sky devoid of radio sources other than our galaxy itself they measured 6.7 degrees (kelvin). Of this, 2.3 degrees could be traced to radiation from the earth's atmosphere and 0.9 degrees to losses and spurious pickup by the antenna. This left 3.5 degrees unaccounted for. This was not a large temperature but Penzias and Wilson were determined to track it down because it was many times stronger than the galactic radiation they had hoped to measure.

Two pigeons had been nesting in the big scoop antenna. They were evicted and their nest and droppings cleaned up, reducing the temperature to about 3 degrees. Penzias and Wilson suspected that poor connections in the antenna might be responsible for this remaining temperature but



The primordial fireball. The universe begins with a great explosion, the "Big Bang", 15 billion years ago. Temperature 10 billion degrees.

Now the fireball has expanded to a radius of about 15 billion light-years. To us, the temperature appears to be only three degrees.



Arno Penzias (left) and Robert Wilson and the giant "sugar scoop" horn antenna with which they found the primordial fireball. A small discrepancy led them to the grandest of all possible answers. (Courtesy of Bell Laboratories)

checks showed nothing amiss. So where did the excess of 3 degrees come from?

After Edwin Hubble had reported his evidence for an expanding universe, about 1930, George Gamow and other thinkers developed theories about how the universe might have evolved during the explosion of a super dense core into a primordial fireball or Big Bang. In 1965 at Princeton University not far from the Bell Telephone Laboratories at Holmdel, New Jersey, Professor Robert Dicke and his associates had been working on such a theory in which the temperature of the primoridal fireball was initially about 10 billion degrees. As the primordial fireball expanded, galaxies and stars condensing in its wake, it gradually cooled down until now its temperature is only a few degrees. The sky in any direction should now have a temperature no less than this. Indeed, Ralph Alpher and Robert Hermann had used Gamow's theory to predict just such an effect. Dicke and his coworkers were unaware of this earlier work, however.

Penzias learned of Dicke's calculations and invited him and his associates to visit their installation. Together they concluded that the elusive 3 degrees measured with the big scoop antenna was due to the residual background radiation from the primordial fireball which created the universe. Thus, even when Penzias and Wilson turned their antenna toward apparently empty regions of the sky, it always received this 3 degree background radiation. This temperature establishes a limit to the sensitivity of all radio telescopes.

In 1931 Karl Jansky had wondered if some weak indications on his radio receiver records might be interference from a nearby power line but he traced them instead to the center of our galaxy 30,000 light-years away.

Now in 1965 two more Bell engineers, Arno Penzias and Robert Wilson, measured an excess temperature of only 3 degrees. They looked for its source in the dirt and poor connections of their sugar-scoop antenna but found instead it was related to the creation of the universe. A tiny discrepancy had led them to the grandest of all possible answers, and in 1978 they received the Nobel prize for their observations.

Jansky discovered the celestial or cosmic radio noise from our galaxy while Penzias and Wilson determined its minimum level from the space beyond.

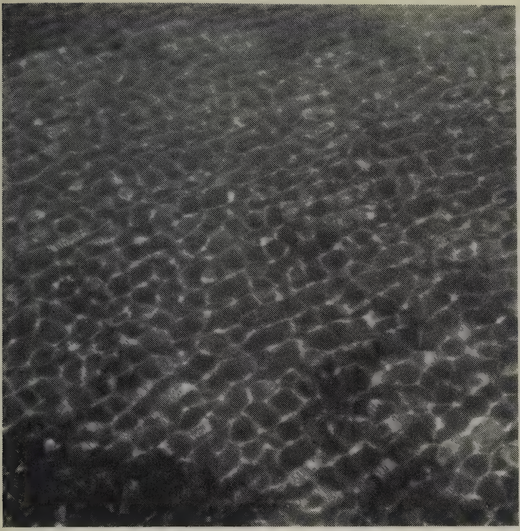
The microwave background radiation from the primordial fireball comes from the greatest distance in the universe, even beyond the quasars, and affords the ultimate in look-back time.

Little Green Men, White Dwarfs or Pulsars?

In 1967 a drama unfolded at the Cambridge University, England, radio observatory which is one of the most exciting scientific events of recent years. The story began in 1965 when Antony Hewish started construction on an array of more than 2000 half-wave dipole antennas set horizontally a few feet above the ground in regular rows covering an area of 4½ acres. Graduate students of the Cambridge University radio observatory helped in the construction. One of these, Jocelyn Bell from Ireland, was responsible for the network of thousands of cables which connected the dipoles with the receiver. The array of dipoles was fixed but by appropriate changes in the cable lengths the response pattern or beam could be shifted in angle in the sky.

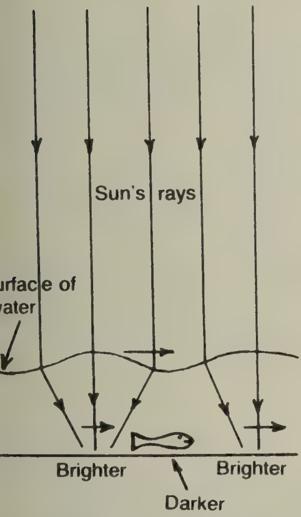
Hewish had designed the system in order to study radio sources of extremely small angular size which tended to fluctuate rapidly in strength or scintillate because of irregularities in the streams of charged particles coming from the sun. The particles of this "solar wind" which envelops the earth can affect the passage of the radio waves. Radio sources of large angular extent do not scintillate but small ones do (angular size less than 1 second of arc). The effect is analogous to that observed optically in which stars, which are mere points of light, vary or twinkle due to irregularities in the earth's upper atmosphere whereas the planets with finite-sized discs do not.

Small waves in the shallow water of a pool produce shadow patterns on the bottom which represent the same kind of phenomenon in action. A minnow sees the sun blinking off and on as the waves pass above him in the same way that stars twinkle or Hewish's radio sources scintillate.

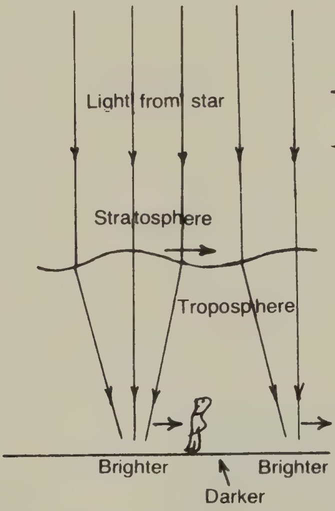


Bright and dark bands on bottom of pool due to refraction of sun's rays by waves.

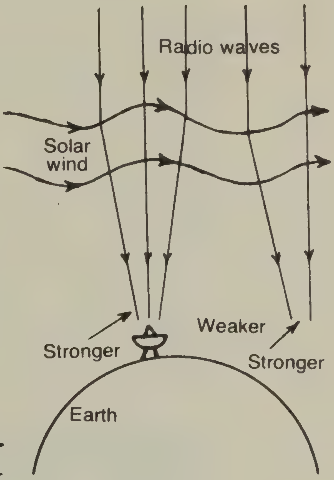
Jocelyn Bell Burnell, who found the first pulsar.



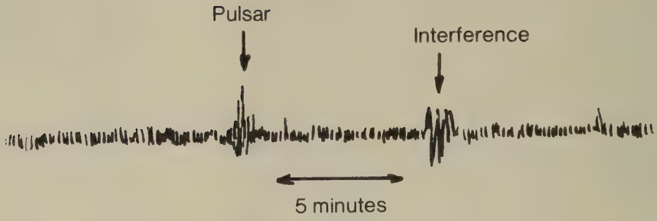
Waves in a pool act as lenses producing brighter and darker (shadow) bands that sweep across the bottom as the waves move. See photograph.



We live at the bottom of an ocean of air, and ripples moving along in the atmosphere make stars twinkle or fluctuate in brightness like the waves in a pool make the sun "twinkle" as seen by a fish.



Radio waves passing through a solar wind (charged particles from the sun) may fluctuate or scintillate like the light from a star twinkles. This is the phenomenon Jocelyn Burnell was studying when she discovered the first pulsar.



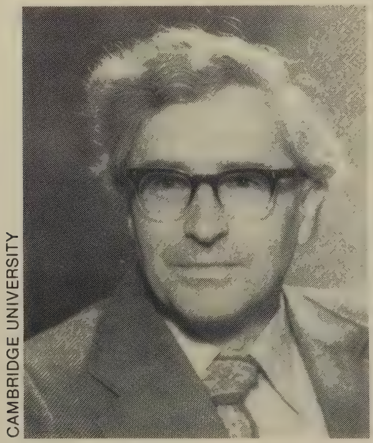
The first indication of a pulsar, "a bit of scruff" and a few minutes later some man-made interference.

By July, 1967, construction of the big array was complete and observations were begun. Jocelyn Bell, then 24, was given the responsibility of analyzing the hundreds of meters of chart paper spewed from the recorder each week in order to note the times of chart deflections having a rapid fluctuation or scintillation.

If the fluctuating deflections came at the same sidereal or star time on succeeding days it would indicate that they were probably due to radio waves from the sky and not from passing trucks, automobiles or airplanes or from a TV or FM station. These true celestial scintillating sources were the ones Jocelyn Bell sought as she struggled to keep pace with the fast outpouring of data but she fell hundreds of meters behind.

In October she noted a peculiar roughness in the record lasting two or three minutes that she called a ''bit of scruff.'' She couldn't classify it readily as either one of Hewish's scintillators or man-made interference.

But, instead of dismissing it from her mind, she thought back and recalled having seen something like it on some records a few weeks previously. Checking back, she found that it had actually appeared several times before and always at the same star time. This persuaded Jocelyn that her scruffy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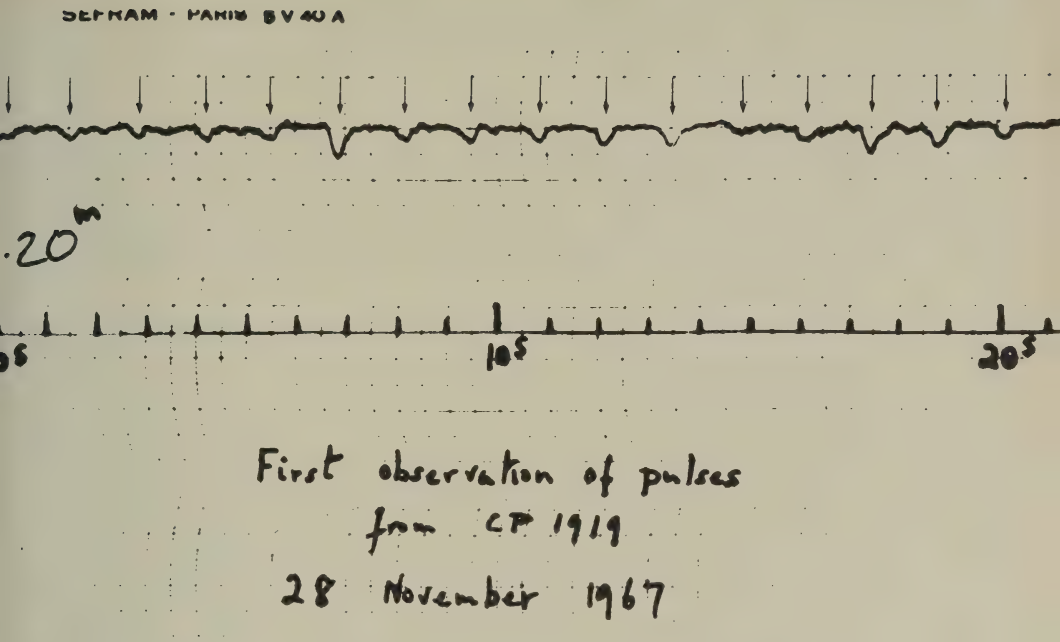
Antony Hewish, who designed and supervised the experiment which resulted in the discovery of pulsars.



First high-speed recording of a pulsar showing pulses at one and one-third second intervals. Arrows indicate pulses. Deflections are down. The lower scale has time marks in seconds.

signals were keeping step with the stars and were indeed from the sky. She discussed the signals with Hewish and they decided to make some special recordings but the source had disappeared! It wasn't until some weeks later, late in November, that Jocelyn caught it again and with a fast recording found that the signal came in a regular succession of pulses spaced almost exactly one and one-third seconds apart. Measurements over several days showed that the pulses maintained this interval with a precision of better than one part in a million!

What could be sending pulses with such astonishing regularity? Hewish knew that white dwarf stars might pulsate but not with anything like this rapidity. It had to be some kind of man-made interference or could it be a beacon signal from an extraterrestrial civilization? Half seriously and half in jest, Hewish and his group labelled the source "L.G.M." for "Little Green Men."

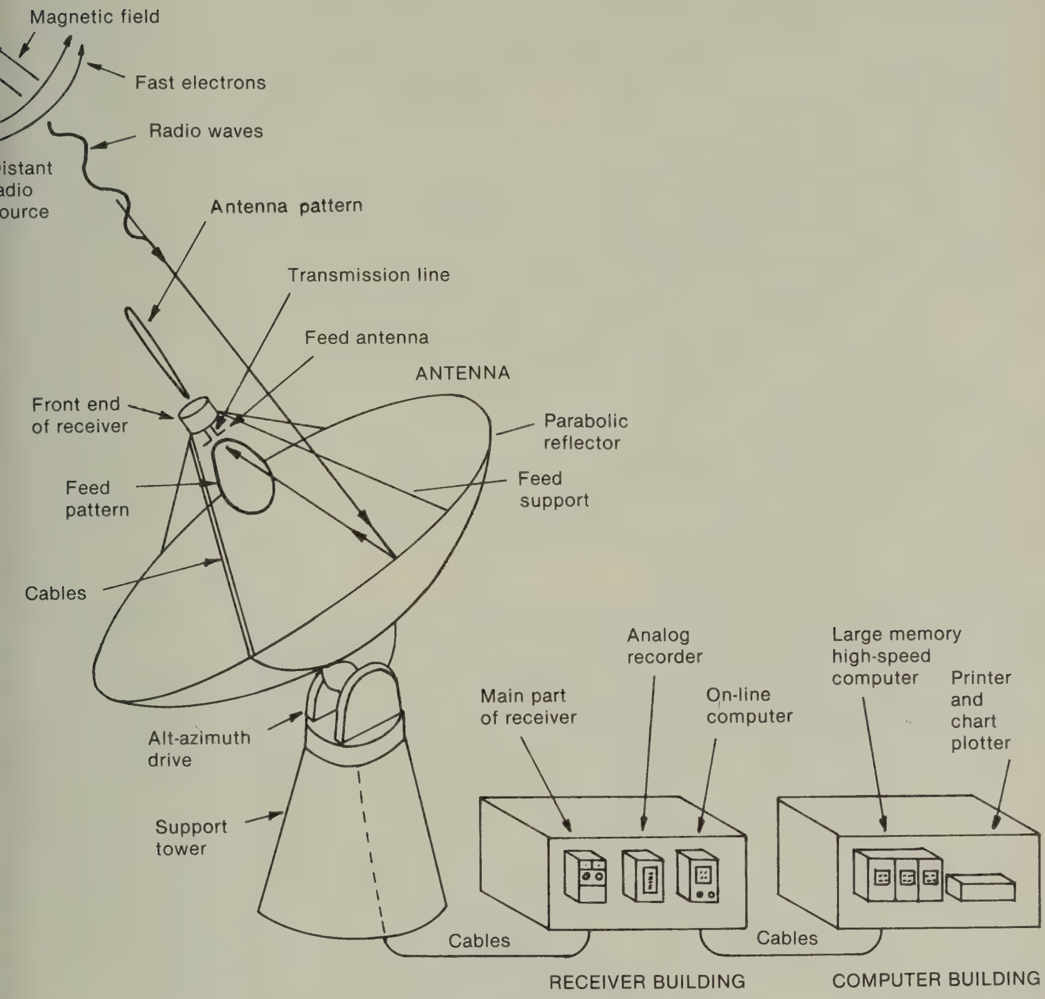
Soon Jocelyn found several more "bits of scruff" coming from other points in the sky and each of these also turned out to be a pulsing source like L.G.M. but pulsing at different rates. Then theory stepped in and it was proposed that the pulses might be produced by a rapidly rotating neutron star.

When the nuclear reactions in a star like the sun cease, the star will collapse due to gravitational attraction and shrink from a diameter of a million kilometers to a few kilometers. Conserving its angular momentum it will also speed up its rate of rotation from, say, once a month to once a second or less. As the star spins it sends out a beam of radio waves from a spot like the beam from a lighthouse, which we observe as a pulse for each revolution of the star. This rapidly spinning star consists of nuclear particles squashed together so densely that a thimble-full weighs as much as 50000 Empire State Buildings.

All thoughts of Little Green Men evaporated and the mysterious signals could be explained as a natural phenomenon from a new class of celestial objects now referred to as *pulsars.* Several hundred of these remarkable objects have been discovered, but none are more remarkable than the one at the center of the Crab nebula, rotating so fast that it pulses 30 times per second—the collapsed relic of the supernova of 1054 mentioned earlier.

Associated with the rotating neutron star are magnetic fields of enormous strength, millions of times greater than any produced on earth.

With appropriate filtering and amplification, the rhythmic pulses of the pulsar sound remarkably like the beat of a hard rock band in a discotheque — a new and different sound from the depths of space coming from super-dense, super-massive, highly magnetized spinning spheres in a bizarre state of matter completely foreign to anything we know on earth.



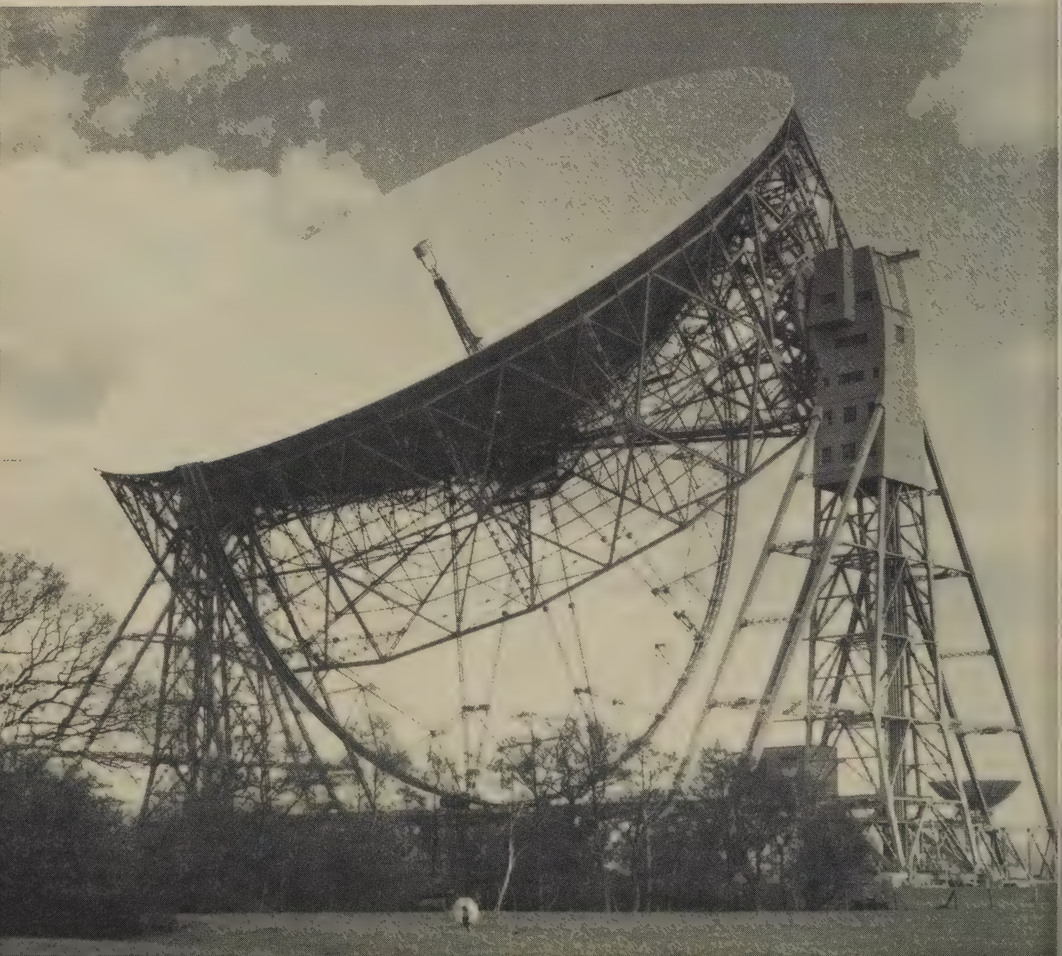
A typical radio telescope. Incoming waves are reflected from the parabola to the antenna at the focus, are amplified and transmitted by cable to the main receiver, recorder and computer.

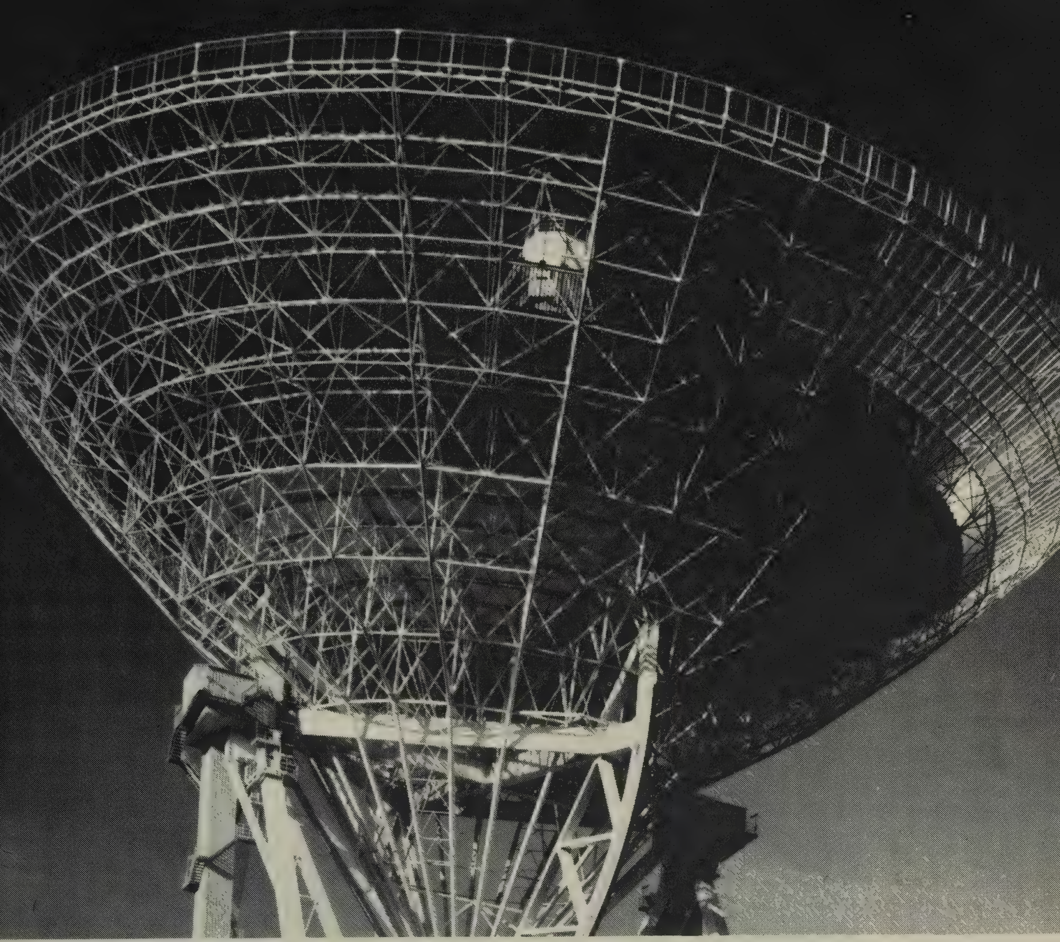
Some Radio Telescopes

Manchester

For over a decade from the time it was completed in 1957, the 76-meter parabolic reflector of the University of Manchester, England, was the world's largest fully-steerable radio telescope. The antenna is on an alt-azimuth mounting with the elevation axis turning on large bearings supported by two high towers while horizontal motion is accomplished by rotating the entire structure on wheels running on a circular railroad track.

The 76-meter parabolic reflector antenna at the Jodrell Bank, University of Manchester, England, radio observatory. For more than a decade after its completion in 1957 it was the world's largest fully-steerable radio telescope. It has an alt-azimuth mounting. (Courtesy of Sir Bernard Lovell)





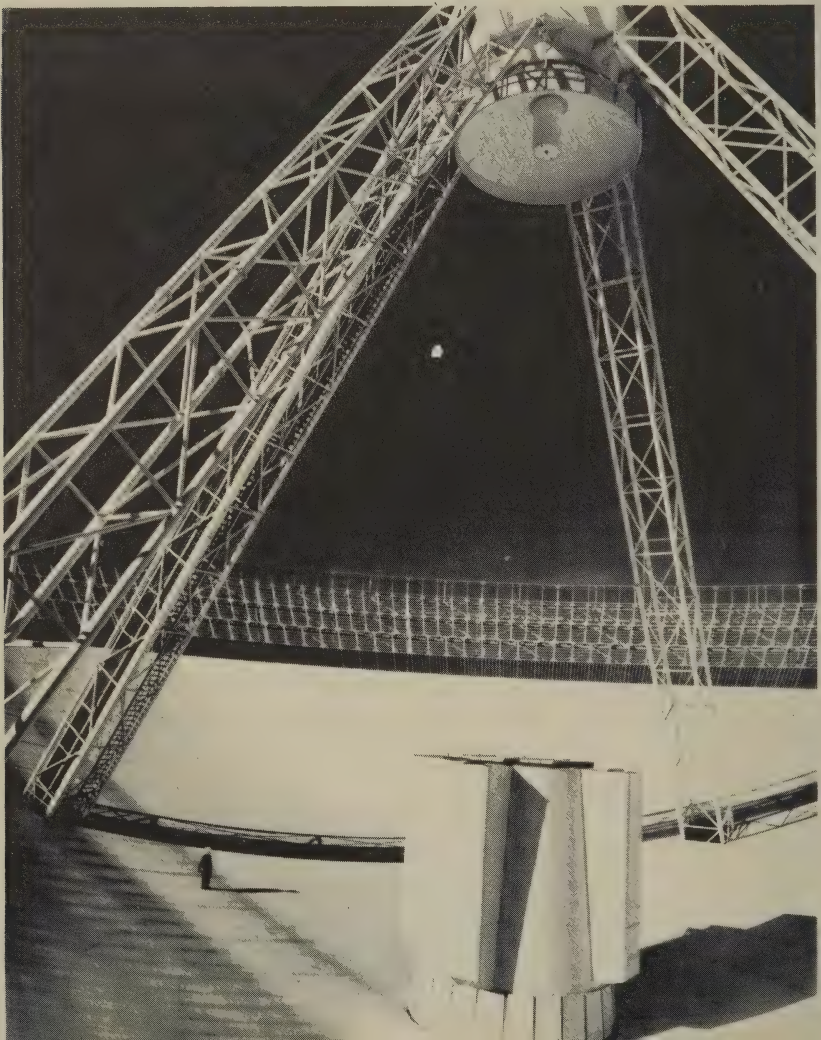
World's largest fully-steerable radio telescope, standing nearly 40 stories tall in a mountain valley near Bonn, Germany. The 100 meter diameter dish and moving parts weigh 3200 tons. The dish can be elevated 20° per minute and the whole structure rotated on a circular track 40° per minute. Note the massive back-up structure required to provide rigidity to the parabola. It can be operated as a prime-focus or a Cassegrain telescope.

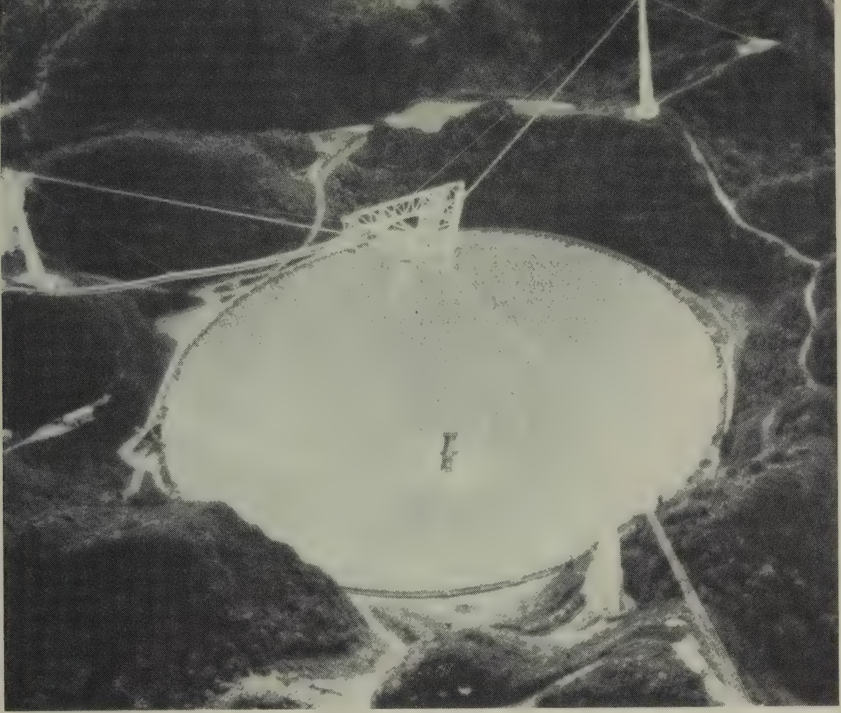
Bonn

In the early 1970s a 100-meter diameter alt-azimuth mounted radio telescope was completed at Bonn, Germany. It is now the world's largest fully-steerable radio telescope. The parabola has a particularly substantial back-up structure which makes operation possible at centimeter wavelengths.

The short wavelength limit of a parabolic reflector depends on the accuracy of the parabolic surface. If the surface has deviations of one-quarter wavelength from the proper position waves reflected from the deviated position travel one-half wavelength more or one-half wavelength less than they should, causing cancellation (crest on trough) and defocusing. Therefore, the parabola surface needs to be accurate to a small fraction of a wavelength, which in practice means better than 1/10 wavelength. Therefore, to work efficiently at a wavelength of 1 centimeter the Bonn telescope needs a surface accuracy of 1 millimeter. The substantial structure of beams and girders of the Bonn telescope help maintain the proper shape for the parabola.

Inside the Bonn telescope. (Note man to lower left for scale.) (Photographs courtesy R. Wielebinski, Max Planck Institute for Radioastronomy)





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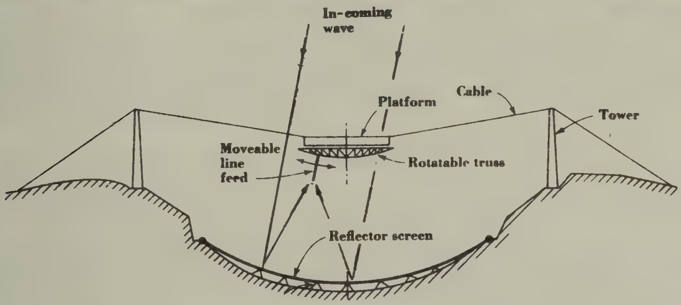


The Arecibo, Puerto Rico, 305-meter spherical dish. Cross-section below. Normally only part of the dish is used at any time and sky coverage is limited to angles about 20 degrees from the zenith.

Arecibo

The largest single dish-type telescope, at Arecibo, Puerto Rico, does not move at all. The dish, 305 meters in diameter, is hung by cables above a mountain valley. To steer its beam to different points in the sky the receiving antenna suspended above it is moved but only about one-third of the total sky can be observed. The dish is not parabolic but is spherical as in a Schmidt telescope. Whereas the Schmidt telescope has a correcting plate for proper focusing, the correcting is done on the Arecibo telescope with an elongated receiving antenna in the focal region. The dish was originally built for studying the ionosphere directly overhead using radar techniques.

Inside the Arecibo dish. (Courtesy of Cornell University)

600-meter diameter radio telescope near Zelenchukskaya, U.S.S.R., called the "RATAN-600." The circle has 895 moveable aluminum panels under the control of an electronic computer. There is also a tiltable flat-reflector with moveable panel along the diameter of the circle. Panels are 7.5 meters tall by 2 meters wide. Waves are focused by the panels on receiving devices near the center, (Tass from Sovfoto).

RATAN-600

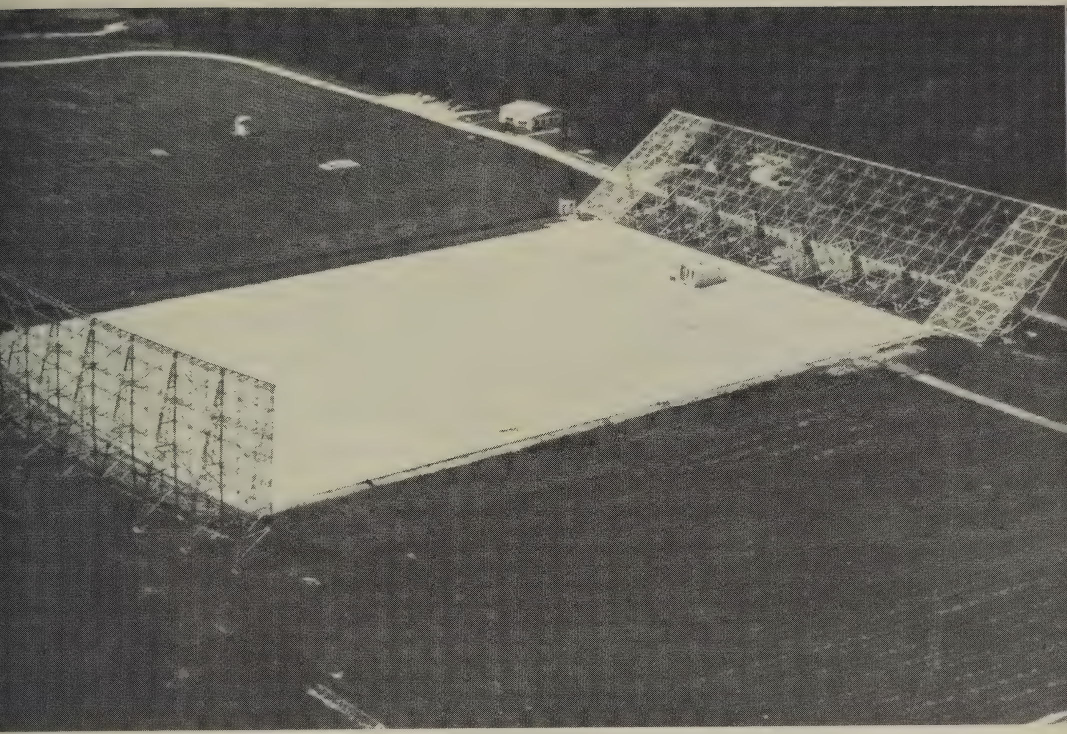
A 600-meter diameter radio telescope was recently completed near Zelenchukskaya, U.S.S.R. Called the RATAN-600 it consists of a 600-meter diameter circle of reflector panels, each of which can be adjusted under computer control, with a large tiltable-flat-reflector almost 600 meters in length situated along a diameter of the circle. Operation can be as a flat reflector-spherical reflector combination or in other modes where the panels around the circle are used to bring waves directly to a focus. This antenna is large enough for the area of 4 Arecibo antennas to fit inside.

Ohio

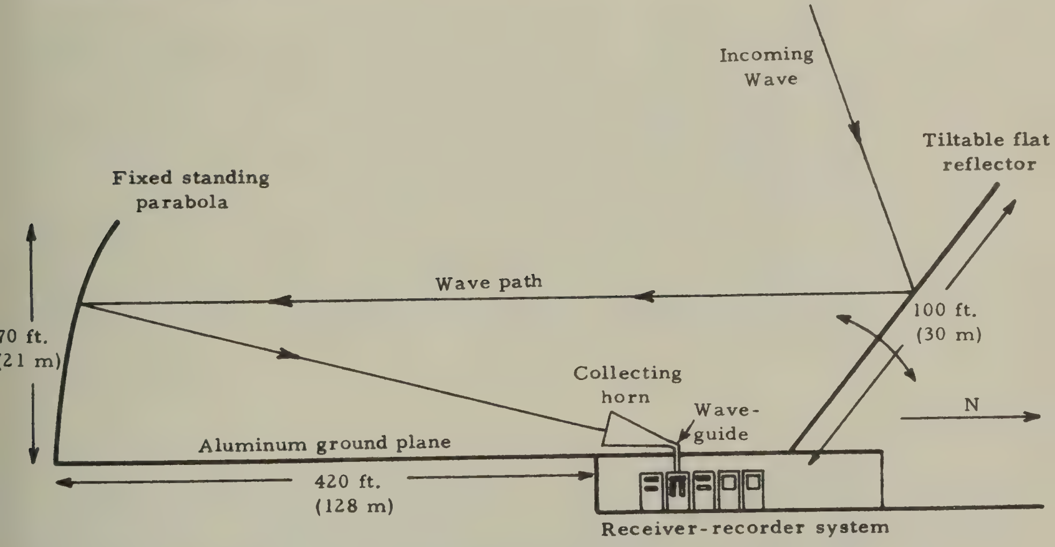
A massive backup structure is required to maintain the parabolic shape of a reflector for all orientations of a telescope. It is needed to prevent the top of the parabola from drooping when the parabolic reflector is vertical (axis horizontal) and the edges from sagging when the parabola is horizontal (axis vertical). The reflectors of optical telescopes are subject to the same deflections. To avoid these problems of structural flexure, the parabolic dish of the Ohio State University radio telescope was built in a fixed standing position on towers mounted directly on the ground. Tower cost increases as the cube of the height so to obtain the largest aperture per unit cost the parabola was made longer horizontally than vertically. A tiltable-flat-reflector deflects waves into the 110-meter parabola and the focal point is at ground level where many different antennas may be deployed for simultaneous operation on many wavelengths. The focal length of the Ohio State University radio telescope is so large that the "parabola" is effectively the same as a spherical reflector. With focal point at ground level, the telescope is also much less susceptible to earth-based sources of interference.

Almost 20000 radio sources were located with this telescope in a sky survey at 21-centimeters wavelength. The quasars OH471 and OQ172, close to the "edge" of the universe, are among the sources discovered as mentioned earlier.

A very large radio telescope at Nancay, France, with 300-meter long reflector and two radio telescopes in Russia including the huge RATAN-600 with 600 meter long tiltable-flat-reflector operate on the same principle as the Ohio State University radio telescope.



110-meter radio telescope of the Ohio State University. A tiltable flat-reflector (at right) deflects the incoming waves into the parabola. Cross-section view below.



Interferometers

To obtain narrow beams of high resolution requires large and expensive structures. High resolution can be obtained without large antennas, however, by means of an *interferometer* arrangement in which two or more smaller antennas are separated by a considerable distance. For instance, two smaller antennas spaced a distance S apart can produce about the same resolution as a single large parabola of diameter S. Lacking the larger collecting aperture, however, the interferometer is less sensitive.

The principle of the *interferometer* will be explained for the simplest possible arrangement: two half-wavelength dipoles separated by a distance S. Waves coming from a distant object along the paths labeled 1 will arrive at the two dipoles (and via equal length electrical cables to the receiver) at the same instant and, therefore, crest adding to crest, will reinforce or be in phase. Waves coming from a distant object along the paths labeled 3 (at an angle Θ with respect to paths 1) will arrive at the right-hand dipole before the left one. Here the difference in path lengths is one wavelength, so a crest will arrive at one dipole at the same instant as a crest at the other and the waves reinforce. However, if the waves arrive at a smaller angle (Θ/2) along the paths labeled 2, a trough will arrive at the left dipole at the same instant a crest arrives at the right one so the waves cancel and the response is zero.

Thus, for waves arriving along paths 1 and 3 the interferometer will have maximum response and for waves arriving along path 2 the response will be zero. There will also be a maximum response for angles of 2Θ, 3Θ etc. and zero response at intermediate angles. The result is a multi-lobed response pattern like the fingers of one's hand. The larger the separation S the larger the number of lobes. If S is many wavelengths the angle Θ is equal to 57 degrees divided by S (in wavelengths). Thus, two dipoles spaced a distance S can produce a beam of about the same width as the beam of a solid reflector of diameter S. However, the interferometer response pattern has many lobes which complicates the interpretation and, of course, it has a smaller sensitivity*.

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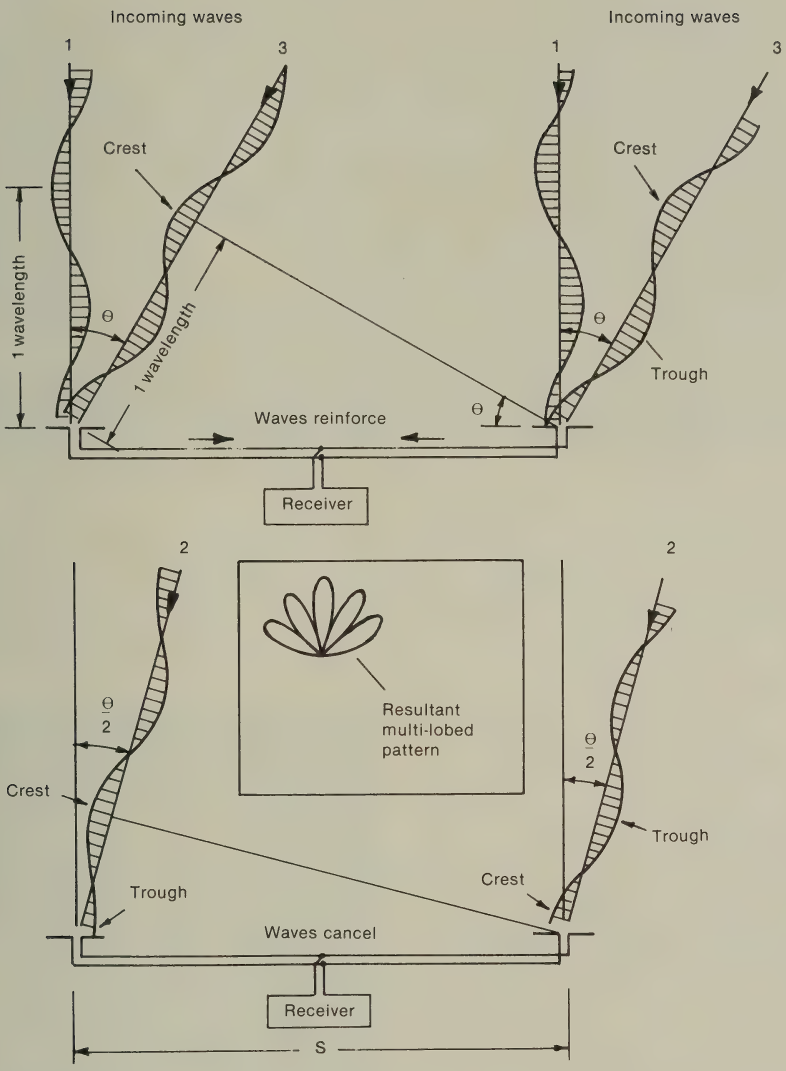
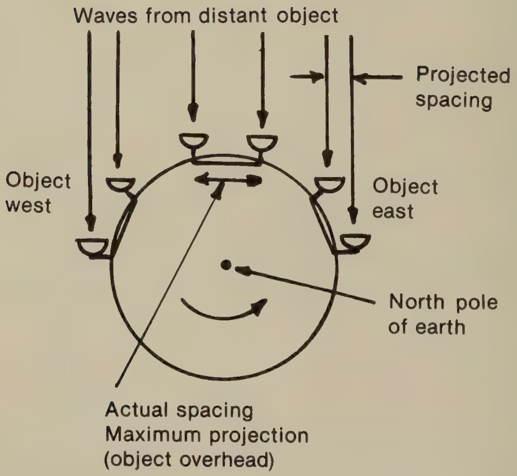
*A more exact analysis yields a factor 2 difference (interferometer resolution angle smaller). However, this is neglected here as trivial compared to our order-of-magnitude interest.



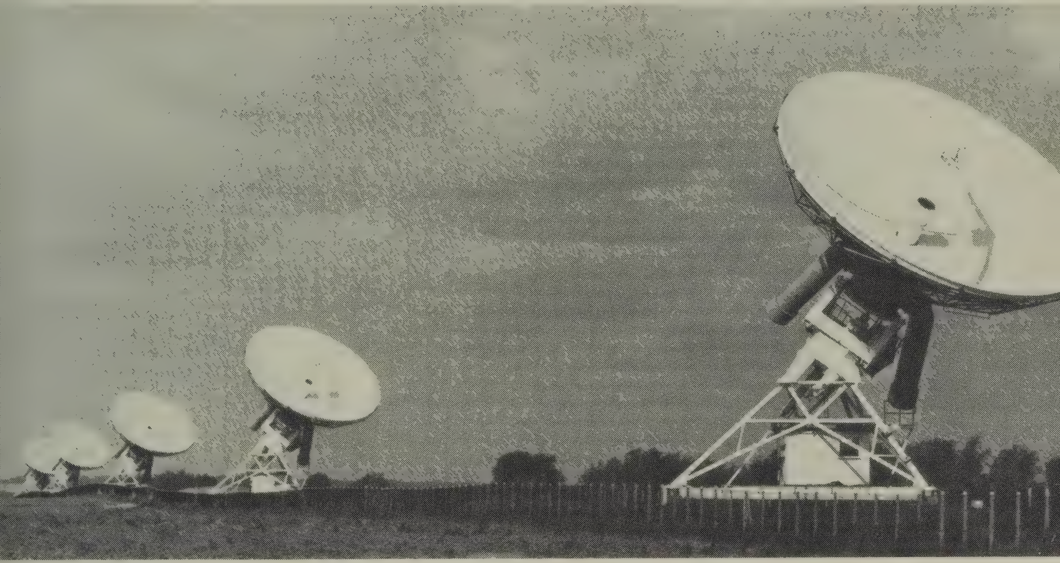
In an interferometer, waves received from directions 1 and 3 (upper diagram) arrive in phase (crests reinforcing) whereas waves from direction 2 arrive out-of-phase (trough cancels crest) (lower diagram). The resulting response pattern is multi-lobed.

Cambridge

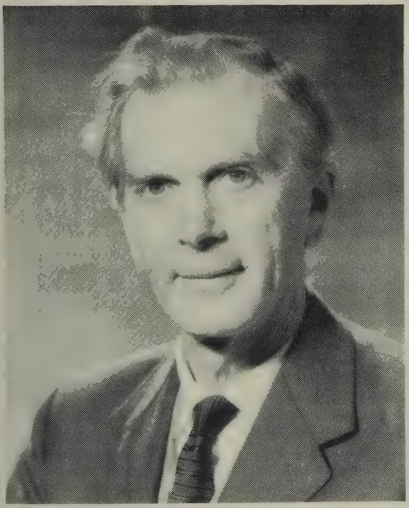
The interferometer principle has been developed to its fullest by Martin Ryle and his associates at the Cambridge University, England, radio observatory in a system called *aperture synthesis.* In one version of Ryle's system a number of parabolic dish antennas of about 10 meters diameter are deployed along a line 5 kilometers long, all connected to a central receiving unit. As the earth rotates the projected spacing between antennas changes and also the angular orientation so that over some hours a variety of spacings and orientations are achieved. Data accumulated in this way are processed by a computer and then displayed in the form of a radio map with resolution equal to that of a radio telescope with a 5 kilometer diameter dish. The antennas are mounted on railroad tracks so that the spacings can be changed when a different resolution is desired. In 1974, Ryle received the Nobel prize for his development of aperture synthesis.



Changes in projected separation produced by the earth's rotation in aperture-synthesis system.



Aperture synthesis interferometer antennas of radio observatory at Cambridge University, England. Eight 10-meter diameter parabolic dish antennas are deployed over a distance of 5 kilometers. It was the first radio telescope to obtain sky detail comparable to that with large optical telescopes on good mountain sites. (Courtesy of Sir Martin Ryle).



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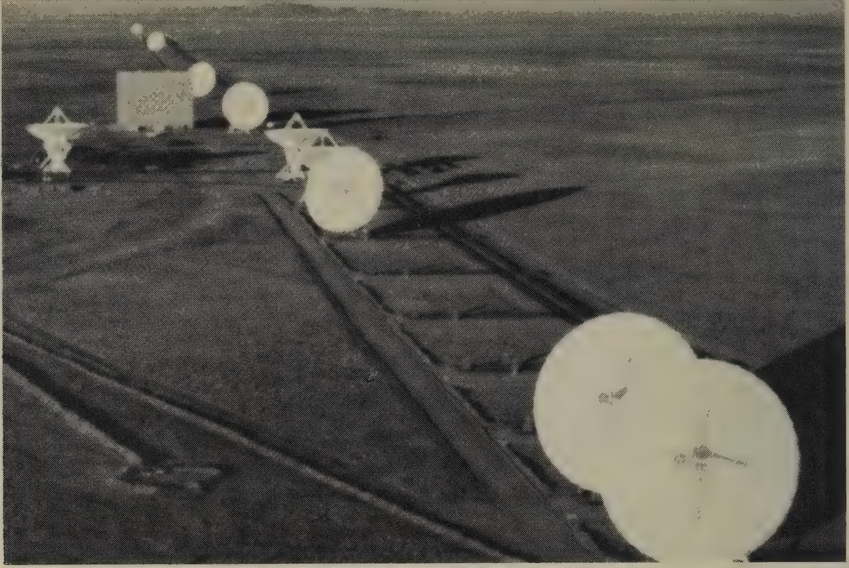
Sir Martin Ryle, father of aperture synthesis.



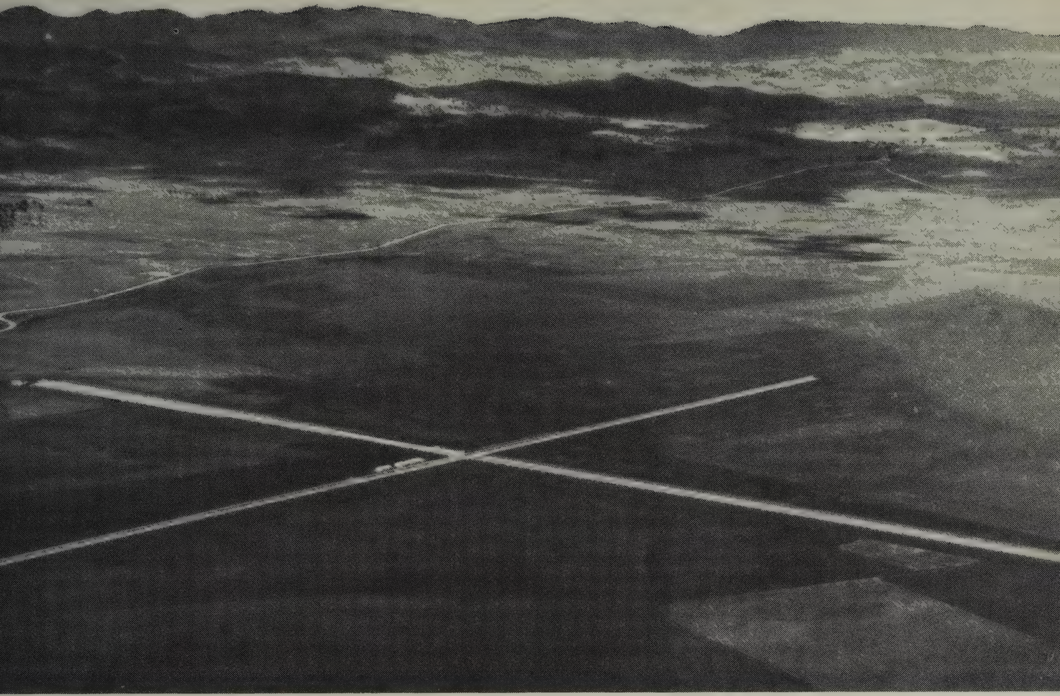
The Very Large Array (VLA) on the Plains of San Augustin, New Mexico, is an aperture synthesis interferometer system with 27 parabolic reflector antenna each 25 meters in diameter. The antennas can be moved along 3 radial spurs of railroad track each 21 kilometers long. Where the railroad tracks cross highways, signs warn motorists, "Caution, Radio Telescope Crossing." (National Radio Astronomy Observatory)

Very Large Array (VLA)

The world's largest aperture synthesis system is situated on the Plains of San Augustin, New Mexico. A total of 27 parabolic dish antennas, each 25 meters in diameter can be moved to positions along a railroad track system of three radial spurs each 21 kilometers long. Working at wavelengths as short as 1 centimeter this arrangement can produce radio pictures of the sky with a resolution of a fraction of a second of arc, comparable in detail to photographs taken with the largest optical telescopes. It would require a solid dish antenna about 27 kilometers in diameter to produce equivalent resolution.

Very Long Baseline Interferometer (VLBI)

Even finer resolution is possible with interferometer antennas separated by intercontinental distances up to the earth's diameter. Big dish radio telescopes in North America have been combined to work as an interferometer system with other large telescopes in Europe and Australia. The earth's diameter (13 million meters) is 130 million wavelengths at 10 centimeters wavelength, providing a resolution angle of one or two thousandths of one second of arc! To date such systems have been able to



The Mills cross radio telescope at Molonglo, Australia, with two arms each 1.6 kilometers long.

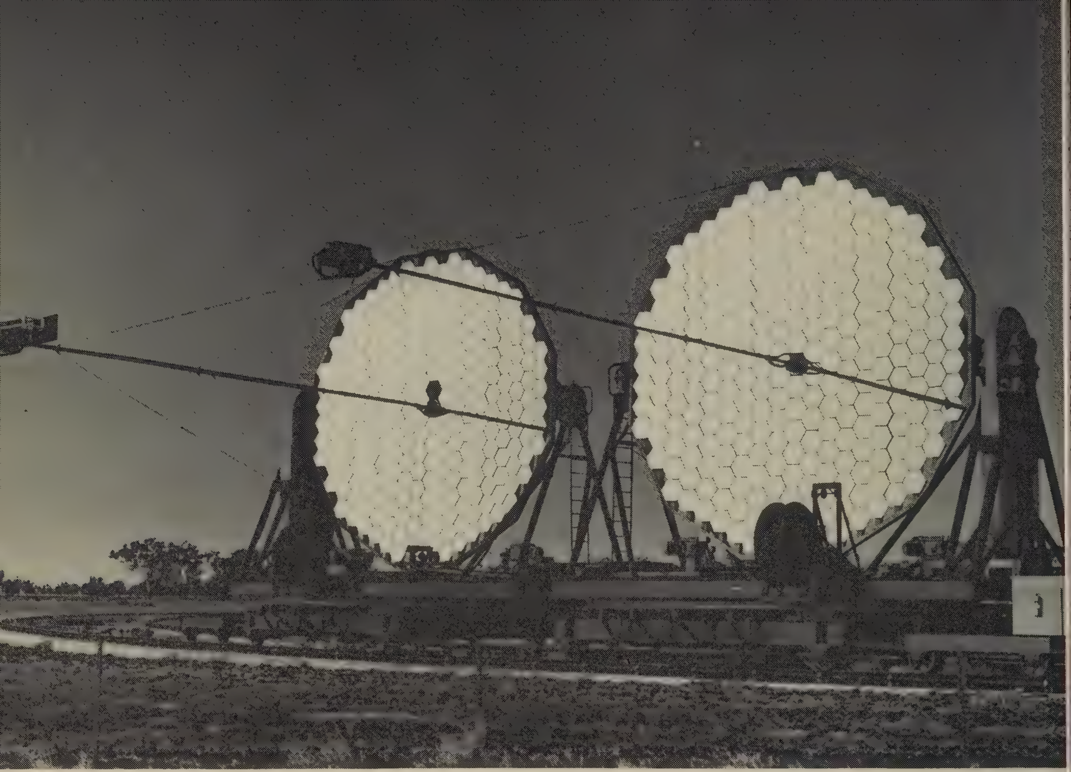
provide information only on the overall size of celestial objects. However, it is hoped that maps showing the shape and extent of objects may yet be possible.

Mills Cross

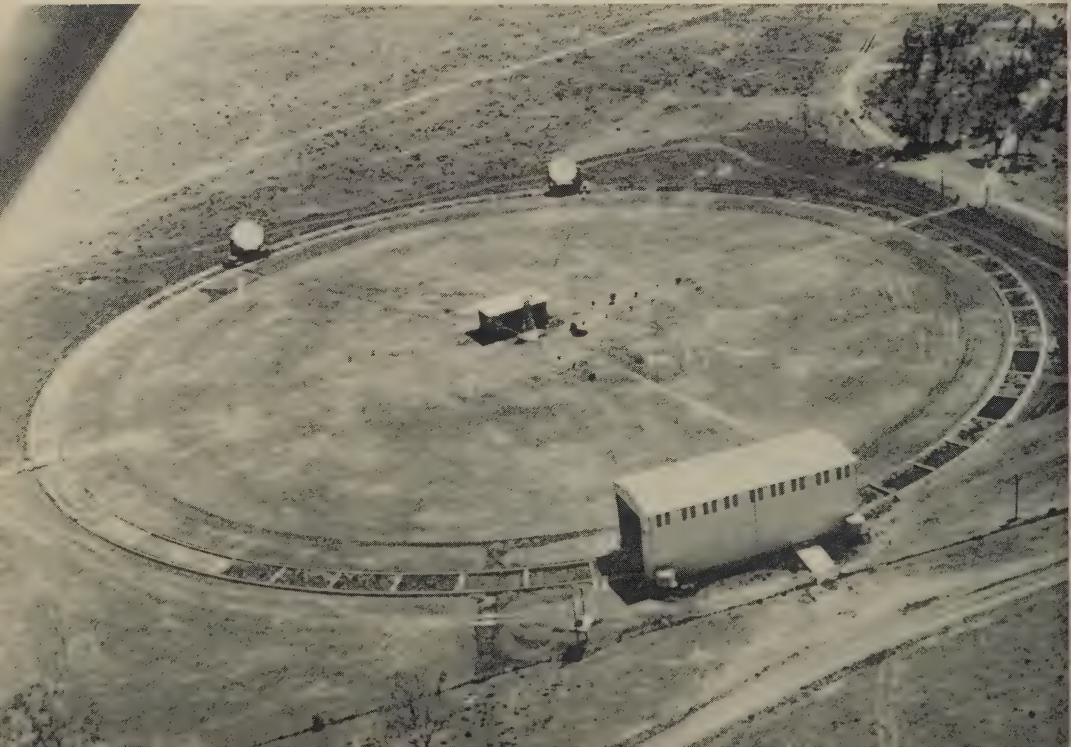
An interferometer arrangement devised by B.Y. Mills of the University of Sydney, Australia, and known as a Mills Cross consists of two long narrow antennas or arms at right angles forming a cross. The largest of this type at Molonglo, Australia, has antennas 1.6 kilometers long and 12 meters wide. The arrangement has the same resolution as a solid or filled-aperture antenna about 1 kilometer square but its collecting area and sensitivity is proportional only to the much smaller area of the actual antenna arms or about 4 percent of a square kilometer.

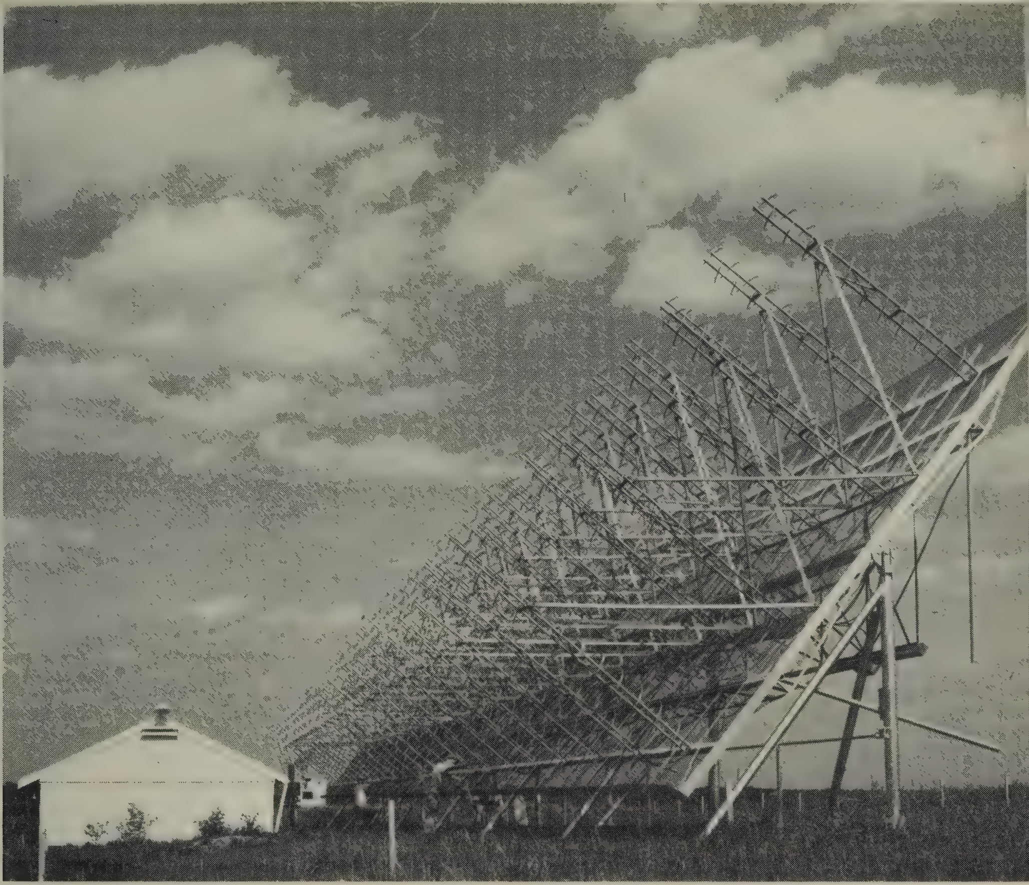
Narrabri

No discussion, however brief, of optical and radio telescopes would be complete without mention of the big optical instrument at Narrabri, New South Wales, Australia, with which the diameter of many stars has been



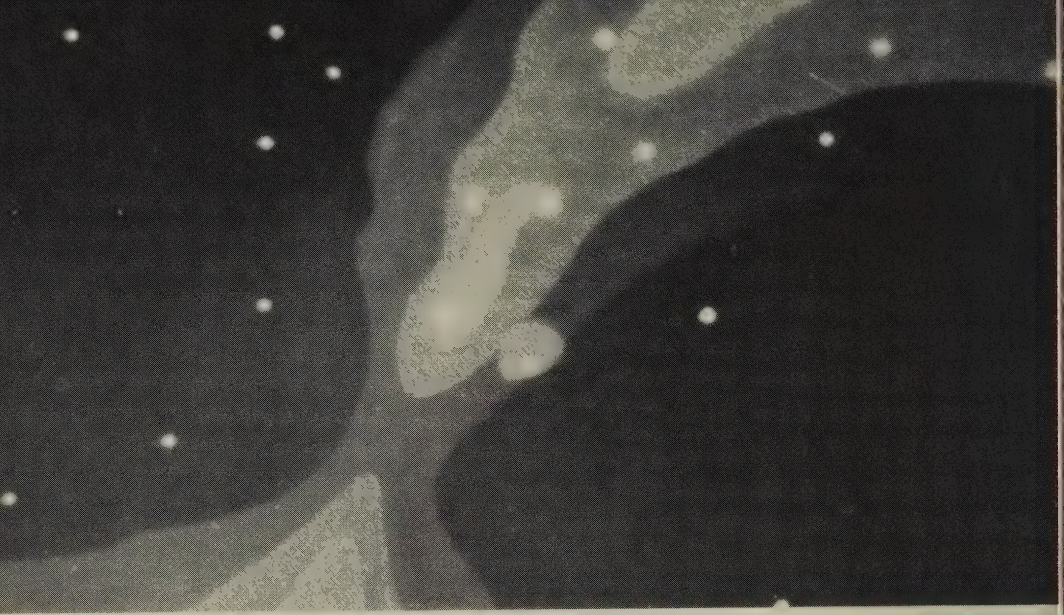
The optical intensity interferometer at Narrabri, Australia, used for measuring the diameter of stars. Each of the two multi-faceted mirrors is 7 meters in diameter. (Courtesy of R. Hanbury Brown).





96-helix radio telescope antenna at the Ohio State University (1953).

measured. Developed by R. Hanbury Brown and Richard Twiss, the instrument consists of two 7-meter diameter multi-faceted, light-gathering mirrors each with a photoelectric detector at its focal point. Each mirror is mounted on a railroad car running on a circular track almost 200 meters in diameter. The arrangement is called an *intensity interferometer,* analagous in many ways to the radio interferometers we have just described. It is unique, however, in that electrical signals are combined *after* detection with the light sensitive device at the focus of each mirror. The phase of the light waves is not compared so the individual facets of each large mirror need be mounted accurately enough only to focus on the detector and not to reproduce a sharp image. In earlier conventional optical interferometers the light from two separated mirrors was combined before detection, a much more difficult procedure. However, the Narrabri system requires that the stars be extremely bright.



This is how the sky would look if our eyes were sensitive to radio waves. The bright arch is the Milky Way or plane of our galaxy. The dots represent radio sources but none correspond to any visible star.

The panorama is a Mercator projection. A more realistic impression would be obtained if the left and right edges were pulled around behind

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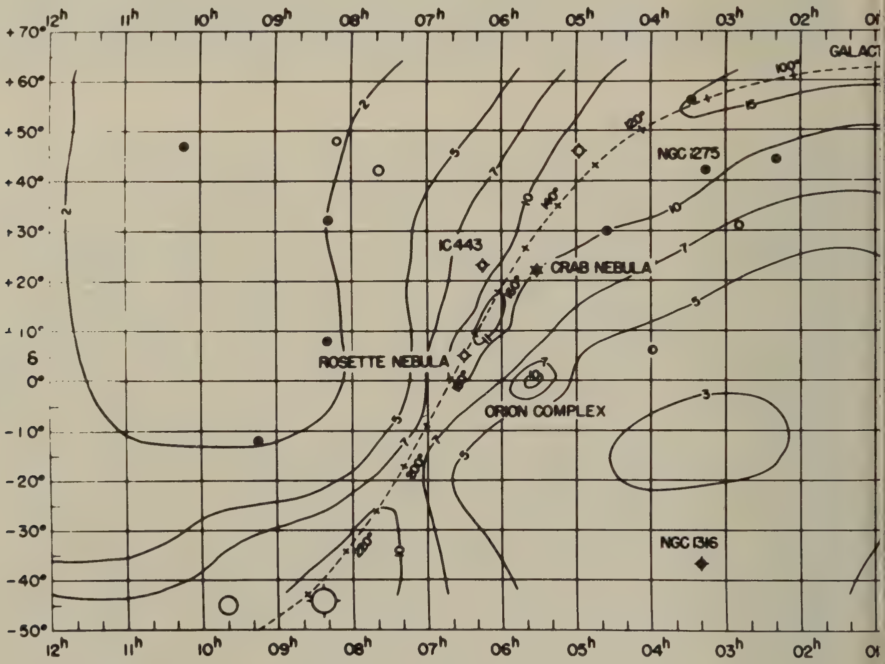
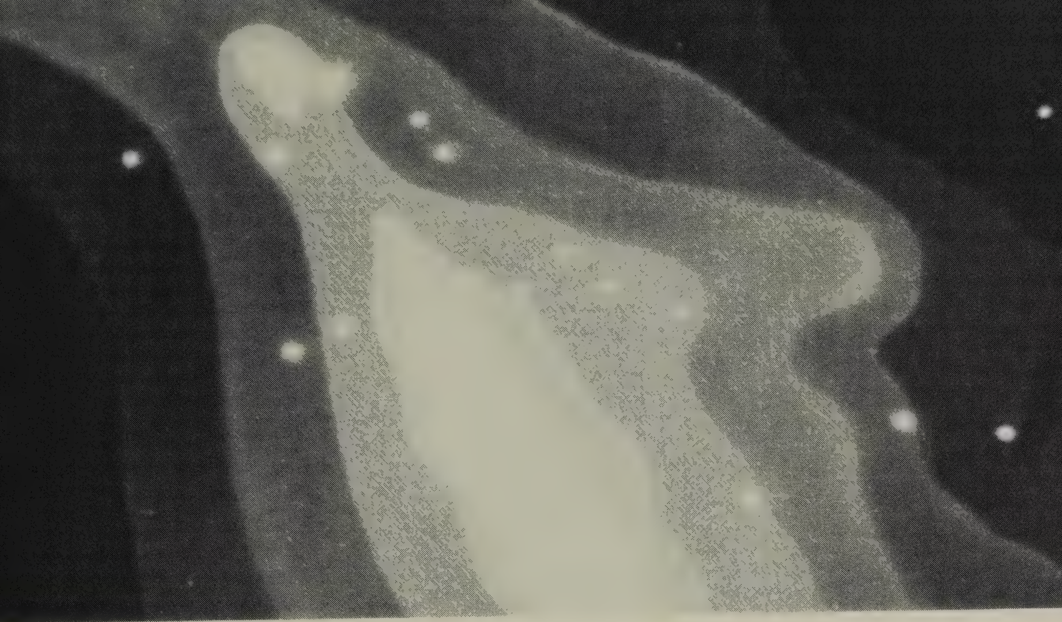
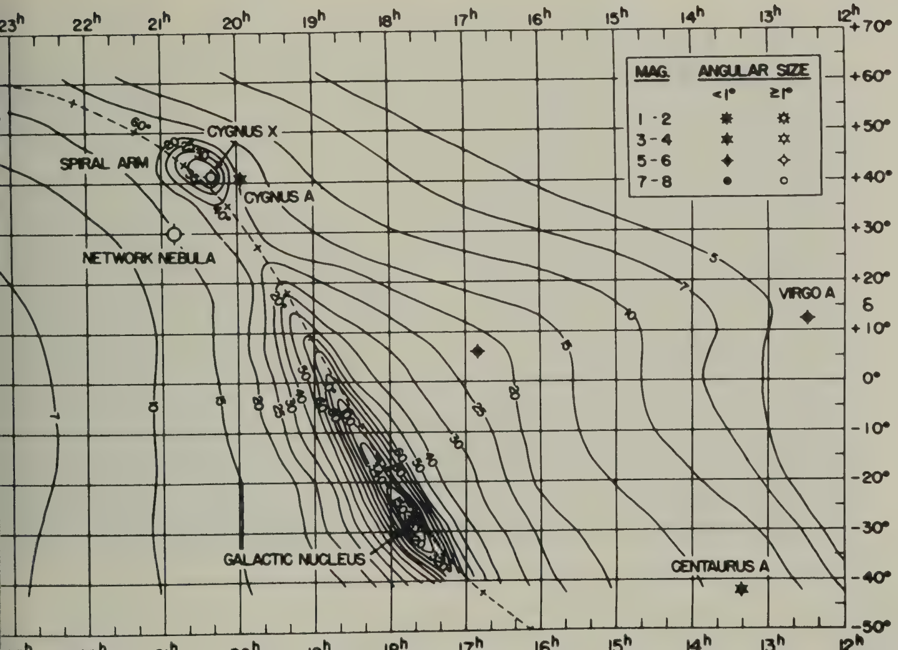
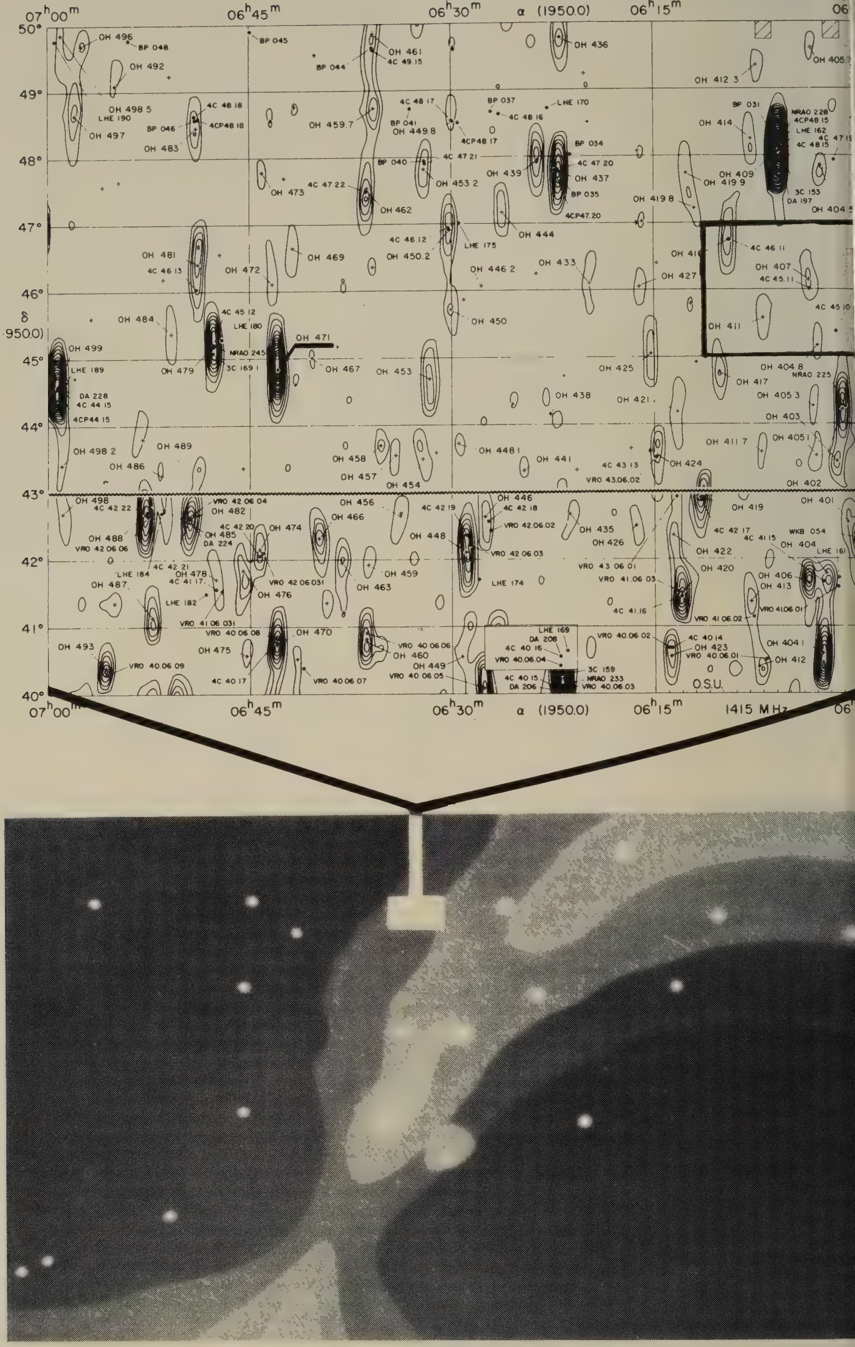




IO SKY

your head and the top stretched over it so that you view the panorama as though it were the real sky above and all around you. The panorama is based on the contour map below, measured with the Ohio State University 96-helix radio telescope at a wavelength of one meter (after Ko and Kraus, 1957).

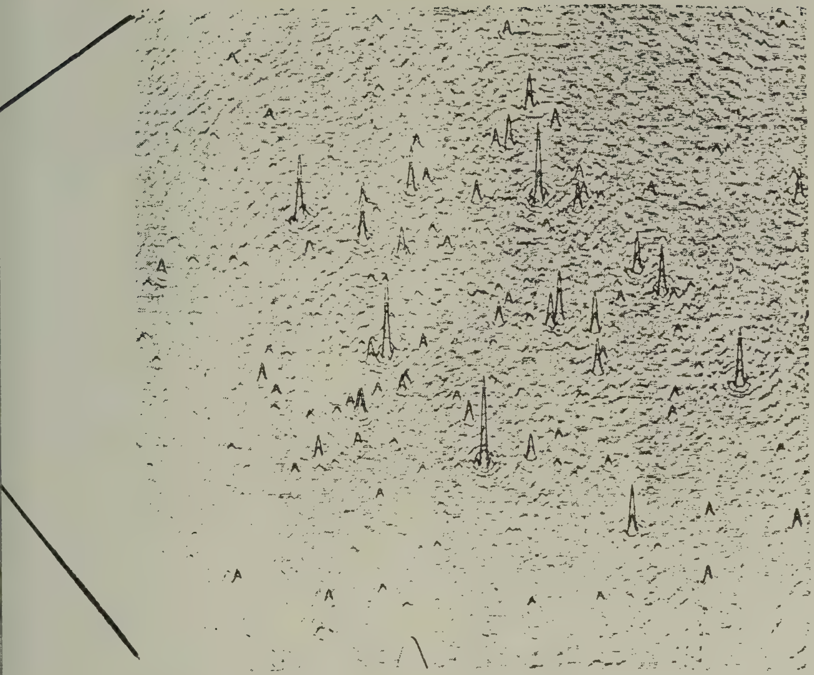


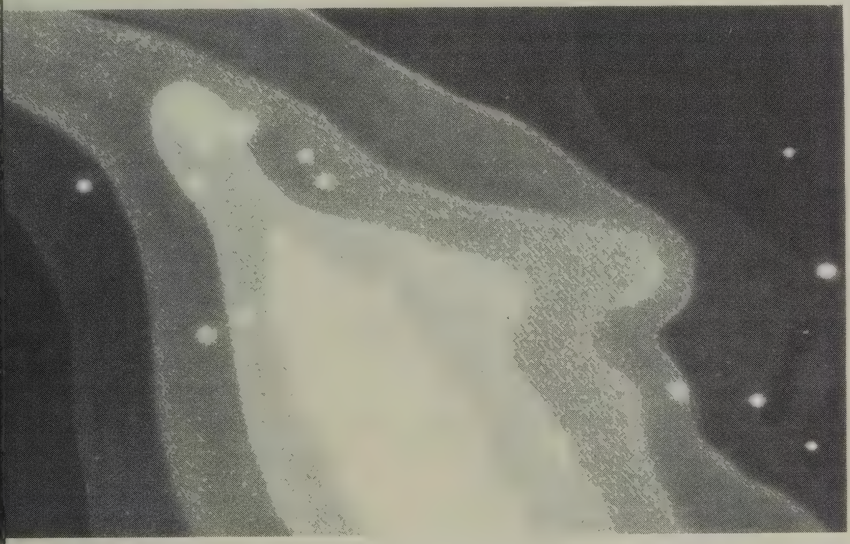


The lower panorama shows how the sky would look if our eyes were sensitive to radio waves. The bright arch is the Milky Way or plane of our galaxy. The dots represent radio sources but none correspond to any visible star.

A small part of the sky at higher resolution is shown at the upper left with radio sources indicated by closed contours. A view corresponding in size to a small section of this map is shown at the upper right at still

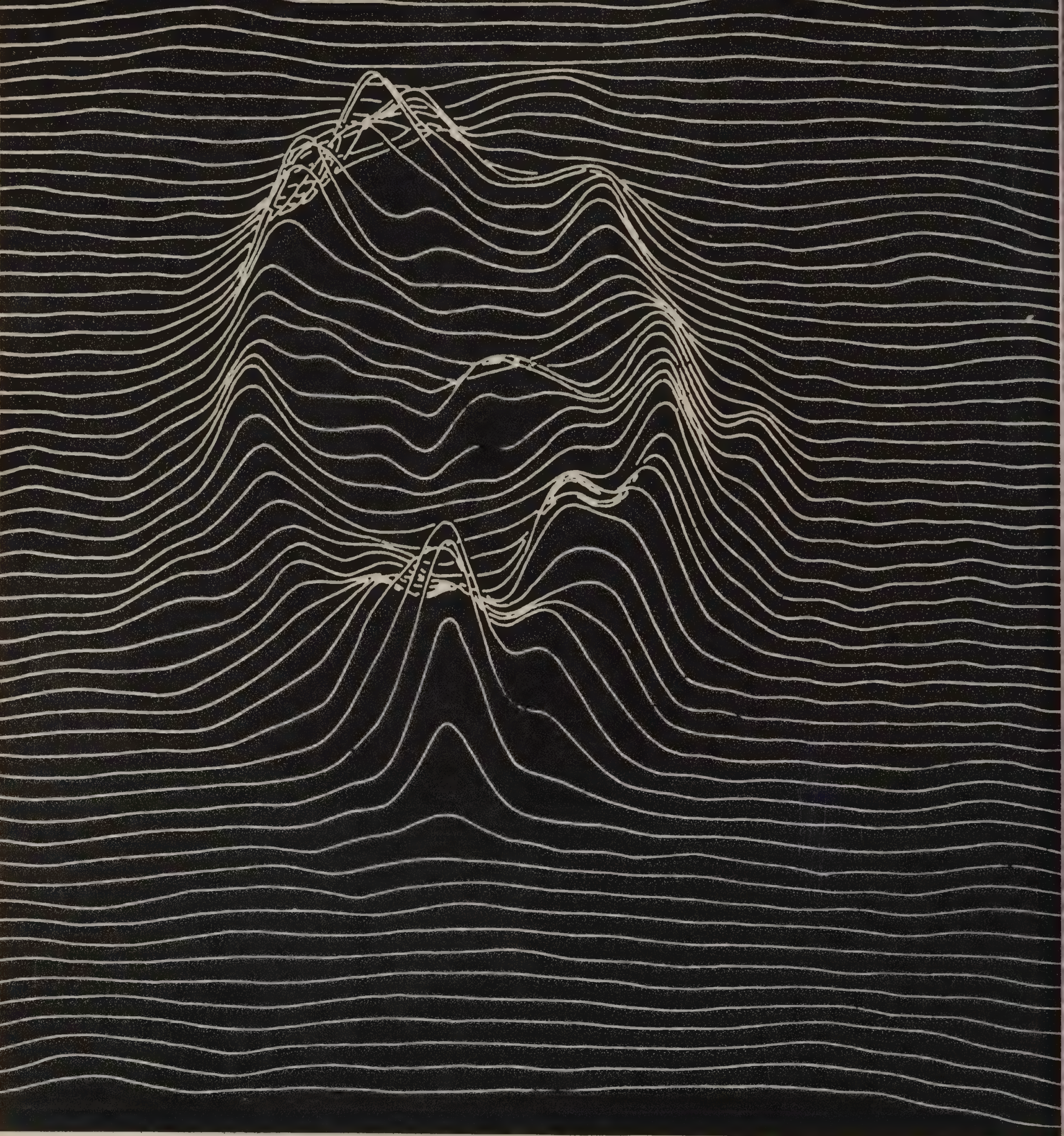
HREE RESOLUTIONS





greater resolution with yet another style of presentation, the spikes indicating radio sources.

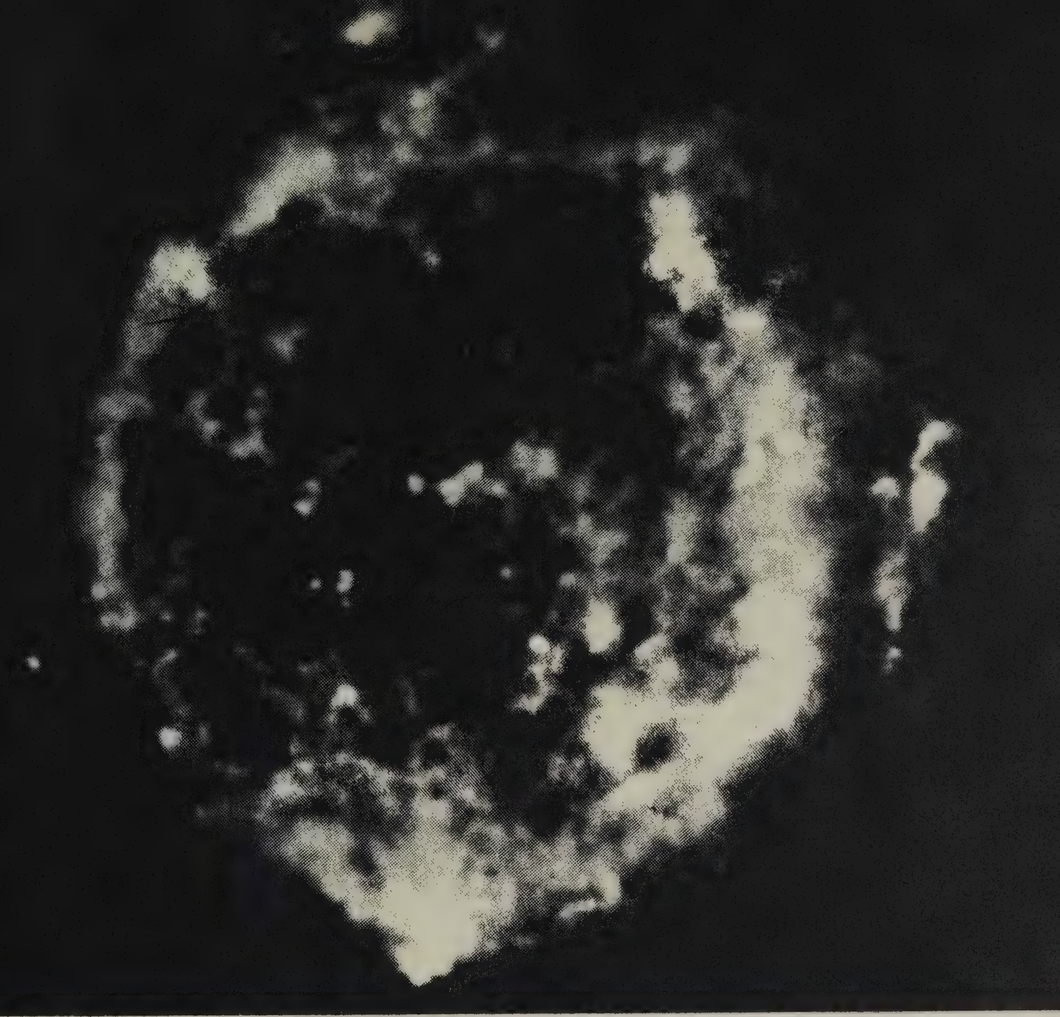
The sky panorama was made with the 96-helix telescope of the Ohio State University, the upper map at the left is part of the Ohio sky atlas made with the Ohio State University 110-meter telescope and the upper map at the right was obtained with the aperture synthesis telescope of the Cambridge University, England. Note the distant quasar OH471 on the map at the upper left.



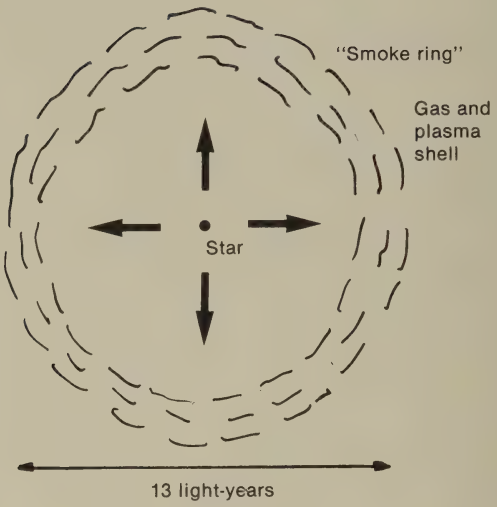
The Cassiopeia A "smoke ring" of radiation coming from material blown outward from a star which exploded about 400 years ago. This remnant of the supernova explosion is about 13 light-years in diameter and it is still expanding at about 3 percent of the velocity of light. Cassiopeia A is about 11 000 light-years distant.

There is almost complete obscuration of the region by intervening gas and dust so that very little can be seen optically. No one recorded seeing the explosion event, as did the Chinese chronicler for the supernova of 1054 A.D., probably because of the obscuration which cuts off the light but not the radio waves.

The profiles were obtained with the Cambridge University aperture-synthesis interferometer. (Courtesy of Sir Martin Ryle)



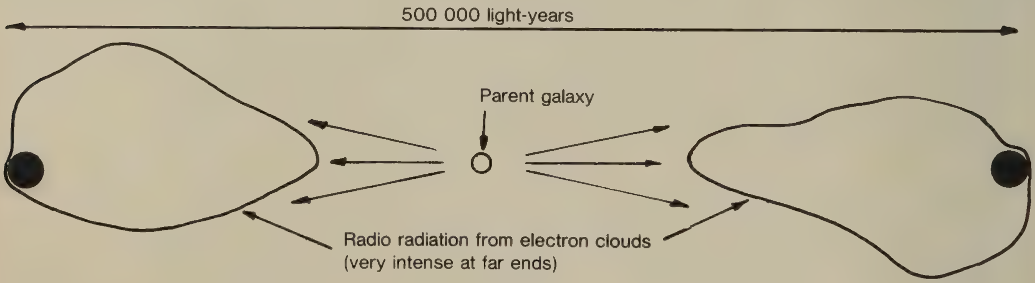
Radio picture showing how Cassiopeia A would appear if our eyes were sensitive to radio waves instead of light. Essentially invisible to optical telescopes, because of obscuration by dust and gas, this billowing cloud is the remnant of a star which exploded about 400 years ago. Picture obtained with the 5-kilometer Cambridge University aperture-synthesis interferometer. Courtesy of Sir Martin Ryle.

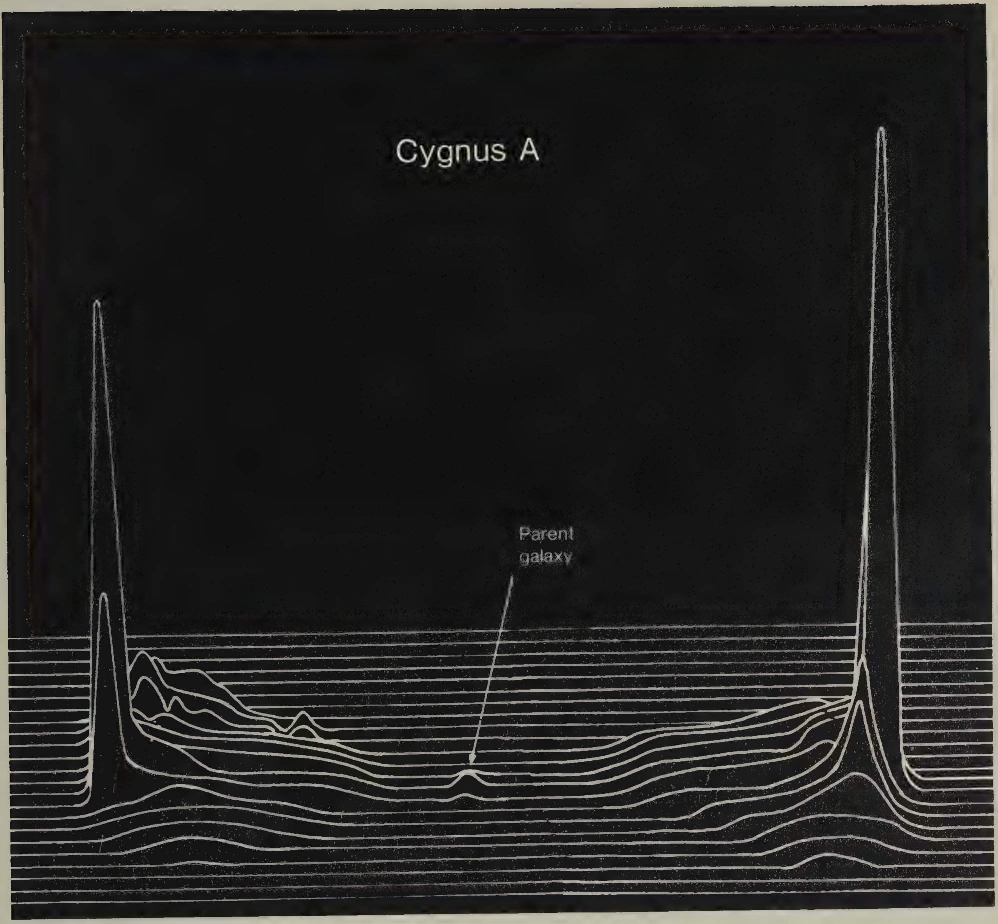


The Cassiopeia A "smoke ring" from a star which exploded 400 years ago.

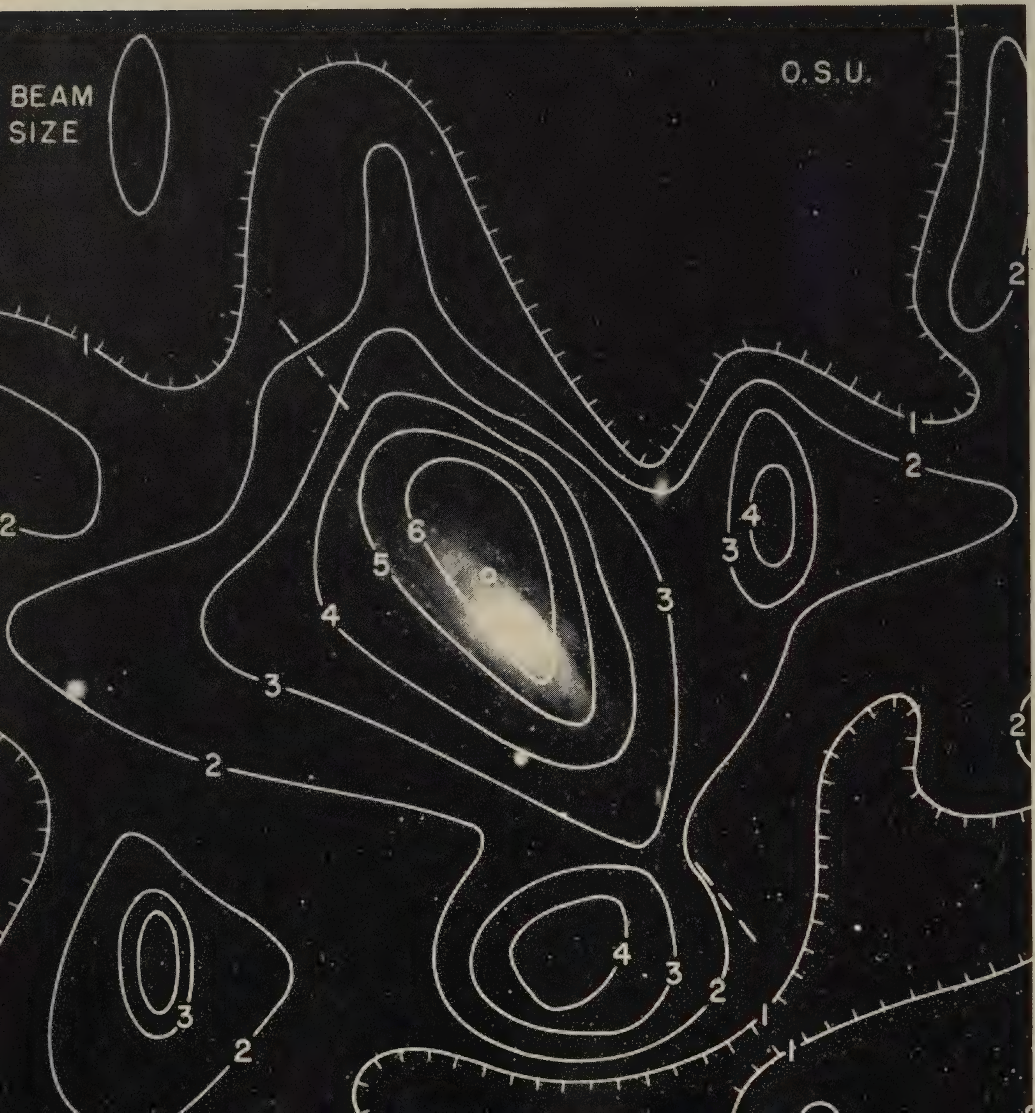
The Cygnus A double radio galaxy produced by a galaxy which exploded millions of years ago. Two huge clouds of electrons were ejected which produce the radio waves. There is little or no light visible from these clouds.

Radio picture of Cygnus A


500 000 light-years
Parent galaxy
Radio radiation from electron clouds (very intense at far ends)

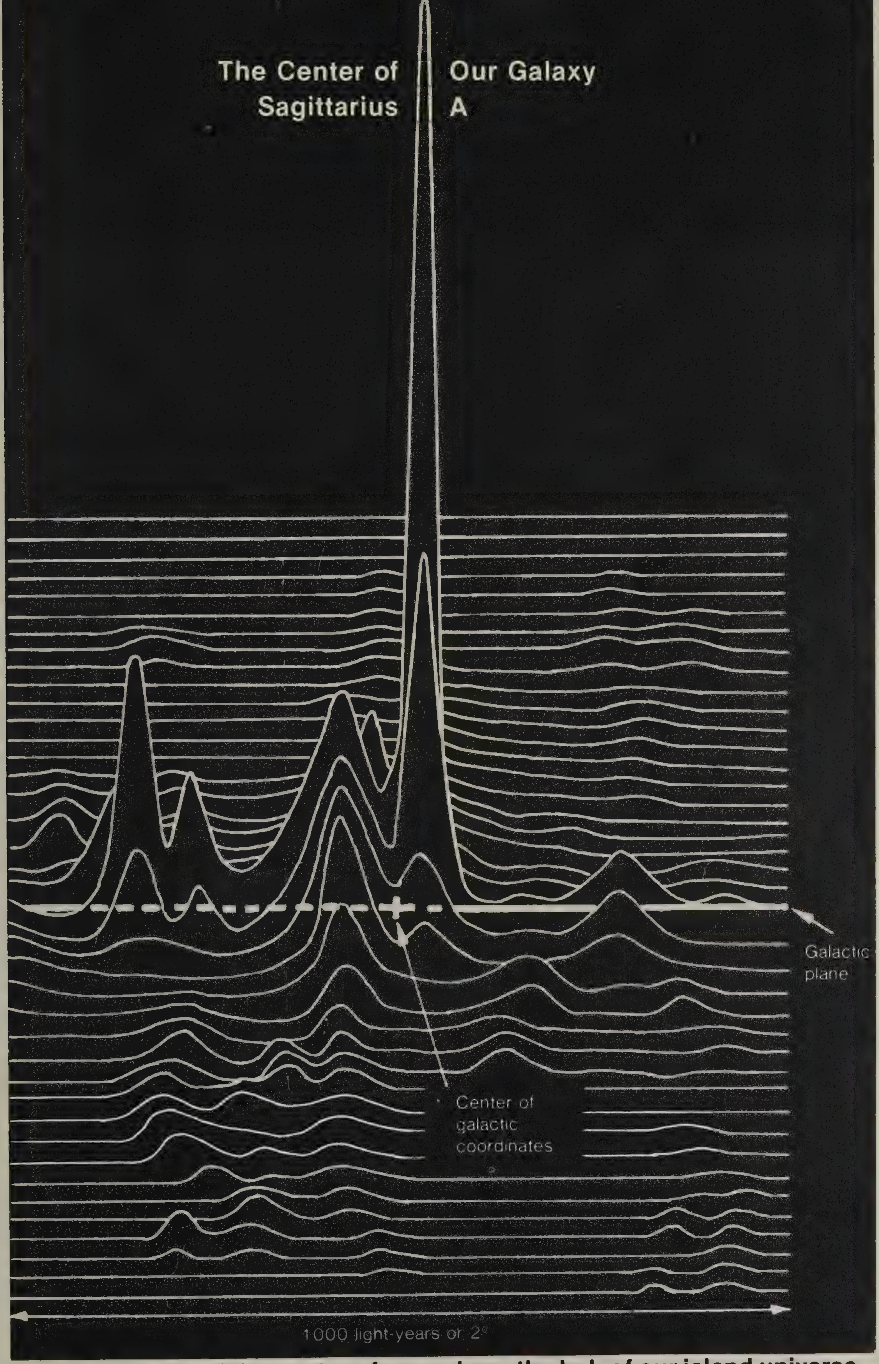


Profile map of the remarkable double radio source, Cygnus A, showing the intense radiation coming from two regions nearly one-half million light-years apart with the parent galaxy midway between. The configuration suggests that the strongly radiating regions are projectiles of plasma shot out in opposite directions from the parent galaxy millions of years ago and still moving apart. The radio emission presumably comes from fast electrons bottled in the plasma by magnetic fields. The profiles are based on a map obtained by Hargrave and Ryle with the 5-kilometer Cambridge University aperture-synthesis interferometer.

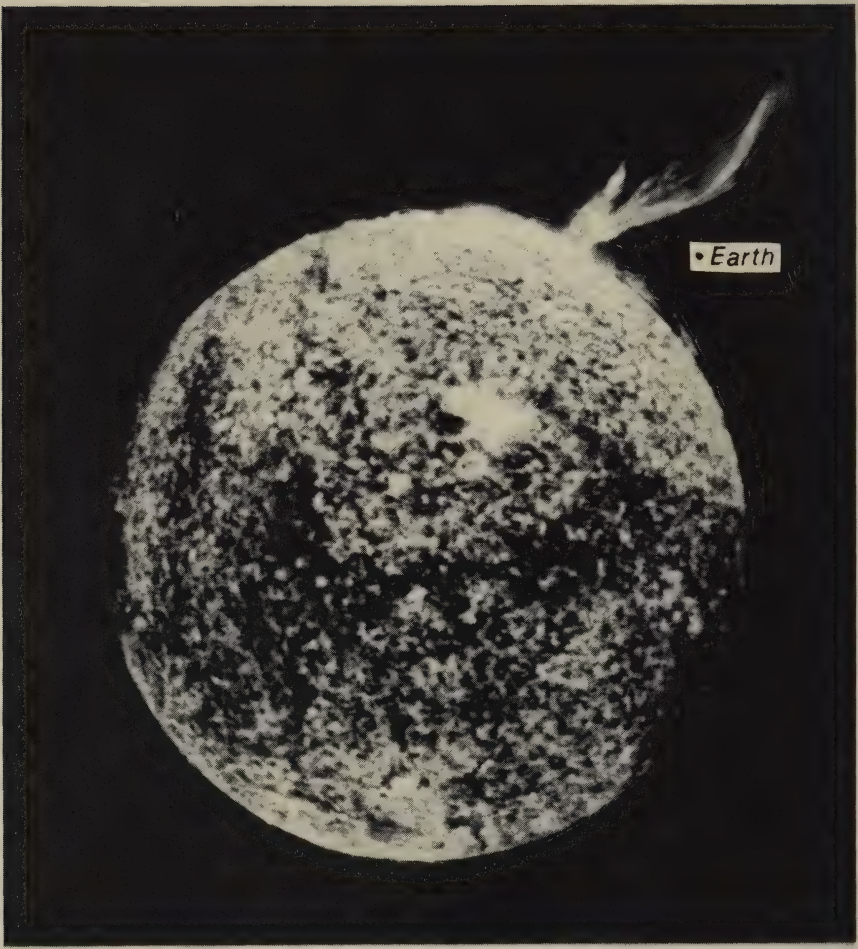


Radio emission from the Great Andromeda Galaxy (M31) compared with its optical appearance. Spurs of radio emission extend far beyond the optical galaxy. They may have been produced by an explosion in the nucleus of the galaxy millions of years ago, ejecting clouds of plasma whose electrons emit radio waves but no light. The Andromeda galaxy is one of the nearest neighboring galaxies at a distance of two million light-years. The visible galaxy is about 100 000 light-years across. Radio contours measured with the 110-meter Ohio State University radio telescope. Photograph taken at the Perkins Observatory.

Note: The word *plasma* is frequently used to describe a region of electrically charged particles, as for example, a region containing equal numbers of electrons (negatively charged) and protons (positively charged).



Profile map of the center of our galaxy, the hub of our island universe around which 100 billion stars including the sun are in rotation. Invisible to optical telescopes because of gas and dust, this radio view shows three intense peaks of radiation standing out from a central hub or core which some astronomers believe contains a very massive black hole. The profiles are based on a map made at a wavelength of 6 centimeters with the 100-meter radio telescope at Bonn, Germany, by Altenhoff, Downes, Pauls and Schraml.



Colossal flare from the sun lashes out like a tongue of flame. View from Skylab with ultra-violet image of sun. Small dot alongside shows relative size of earth. (Courtesy of NASA).

Solar Winds and Solar Gales

Our nearest star is the sun. To us on the earth it is a vital star, providing us with heat and light. Our distance from the sun (150 million kilometers) seems to be optimum, giving an environment conducive to life that is neither too hot nor too cold. The sun's heat is produced by a fusion process in which hydrogen is converted to helium with attendent release of energy. The sun is over a million kilometers in diameter and is about one million times more massive than the earth.

The earth revolves around the sun once per year and the sun rotates on its axis once in about 26 days. Galileo was the first to deduce that the sun rotated, when in 1611, he observed spots on the sun and noted that over a period of days they moved. The sun is of great interest to astronomers because it is the only star close enough to be studied in any great detail. It is a rather average star of the yellow-dwarf class (temperature about 6000 kelvins) and on a power-temperature or Hertzsprung-Russell diagram (page 53) is situated toward the cooler, fainter end of the principal star group called the main sequence.

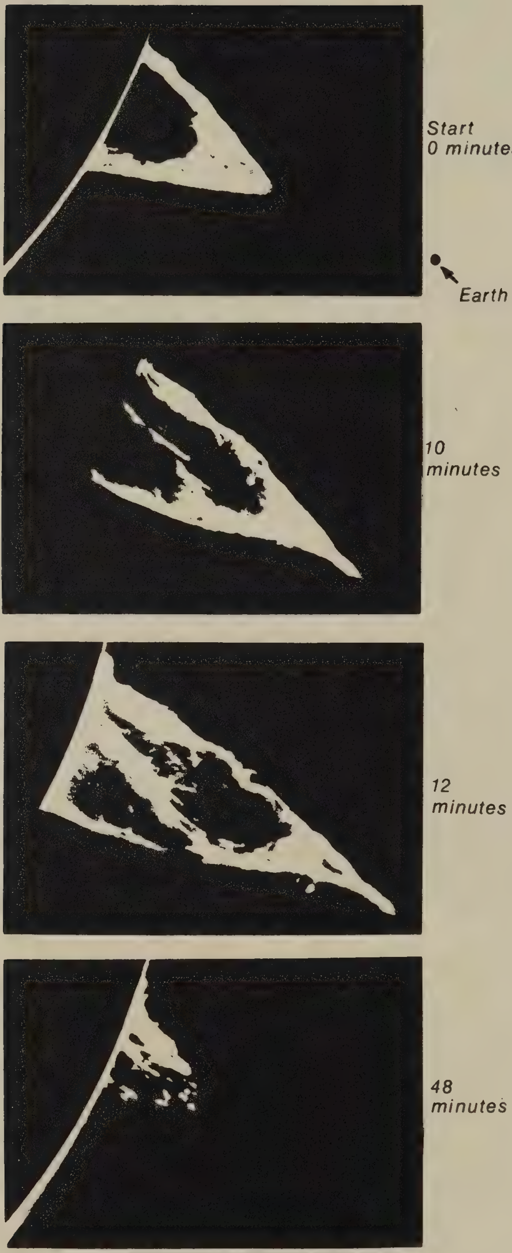
The visible disc of the sun is called the *photosphere.* Above the photosphere lies the *solar atmosphere.* The lower part of the atmosphere extending up to several thousand kilometers is called the *chromosphere.* Above it is the upper atmosphere or *corona* which extends to very great heights. During a solar eclipse the corona is observed to extend optically to at least one million kilometers (one solar diameter) above the photosphere. At radio wavelengths the corona extends much further than this. It contains electrons and protons that are of appreciable numbers even beyond the earth. These particles stream away from the sun producing a *solar wind.*

At times spots appear on the disc of the sun. They appear dark because they are at a lower temperature than the surrounding photosphere. By observations of the Zeeman splitting of spectral lines it has been determined that there are intense magnetic fields around the spots. The number of spots on the sun follow a slowly-varying trend with an 11 year cycle, from a maximum number through a minimum and back again to a maximum in 11 years.

The heat and light output from the sun is relatively constant and provides a steady power of about 1400 watts per square meter at the distance of the earth. Although, the radio power output of the sun is very small by comparison (down a million-billion fold) it is highly variable, tending to increase during sunspot maxima and to reach very high levels, up perhaps a million fold, for short periods during eruptions or outbursts.

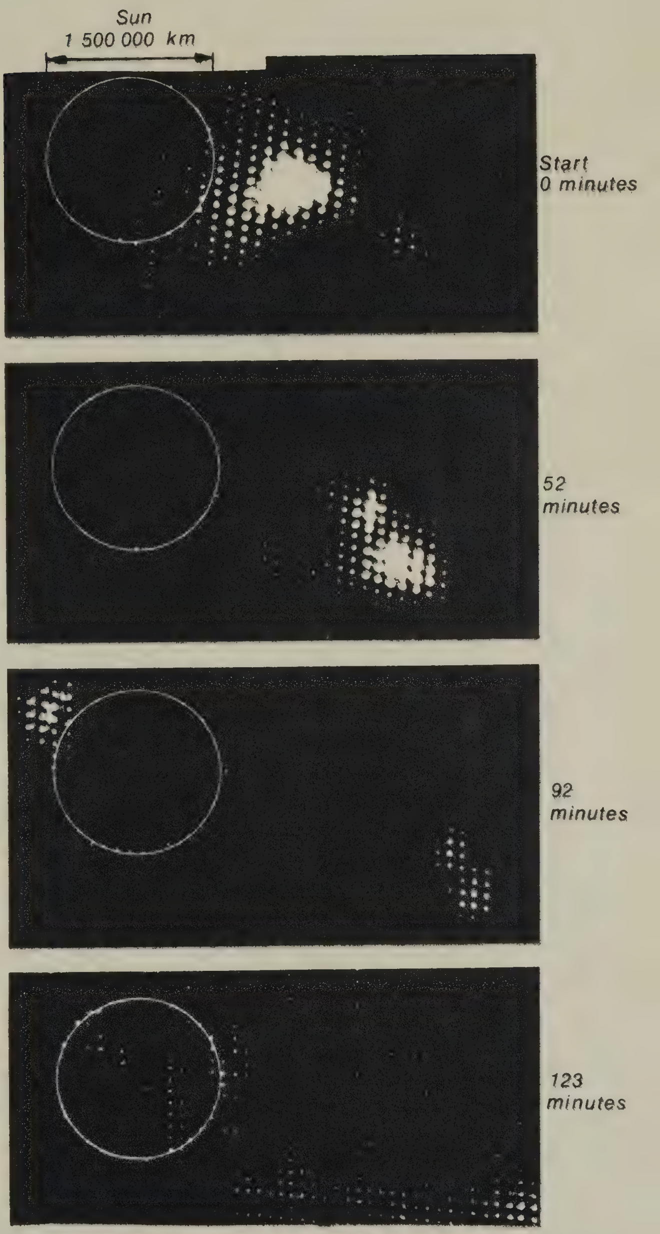
The accompanying set of four photographs shows the progress of a solar eruption from start to finish as photographed by Joseph Klepesta at

SOLAR OPTICAL FLARE



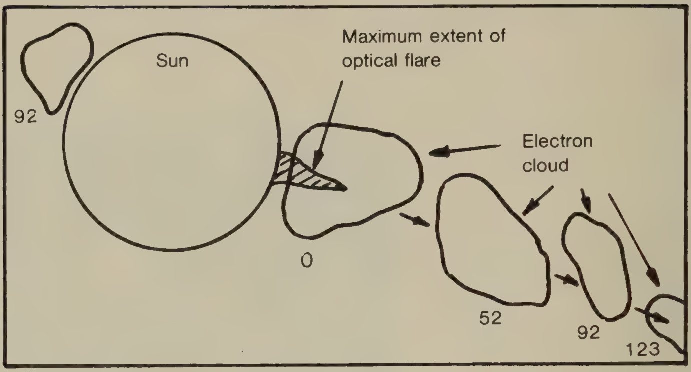
Solar flare or eruption photographed 10, 12 and 48 minutes after the first picture (at top). Maximum height of flare is 500 000 kilometers. Note size of earth shown for comparison. (Photographs taken April 11, 1959, by Joseph Klepsta, Prague, Czechoslovakia).

SOLAR RADIO FLARE



Radio emission from a cloud of charged particles (electrons and protons) ejected during a great solar flare on the sun March 1, 1969, as recorded in the manner of a photograph by rapid scanning with the radio telescope at Culgoora, Australia. The four frames show the rapid progress of the cloud from ejection (0 minutes) to the edge of the frame two hours later. The ejection velocity was nearly two million kilometers per hour. The cloud swept past the earth a couple of days later as a blast of solar wind.

Note that in the third frame (at 92 minutes) intense radio emission occurred on the opposite side of the sun from the flare. The white circle outlines the sun (1 500 000 kilometers diameter).



Composite of optical and radio pictures showing progress of solar eruption with numbers indicating minutes after start (0 minutes) for each cloud position.

Prague, Czechoslovakia, on April 11th, 1959. The second, third and fourth photographs were taken 10, 44 and 48 minutes after the first one. Such events are accompanied by strong radio emission. Note the smallness of the earth, shown alongside for comparison of size.

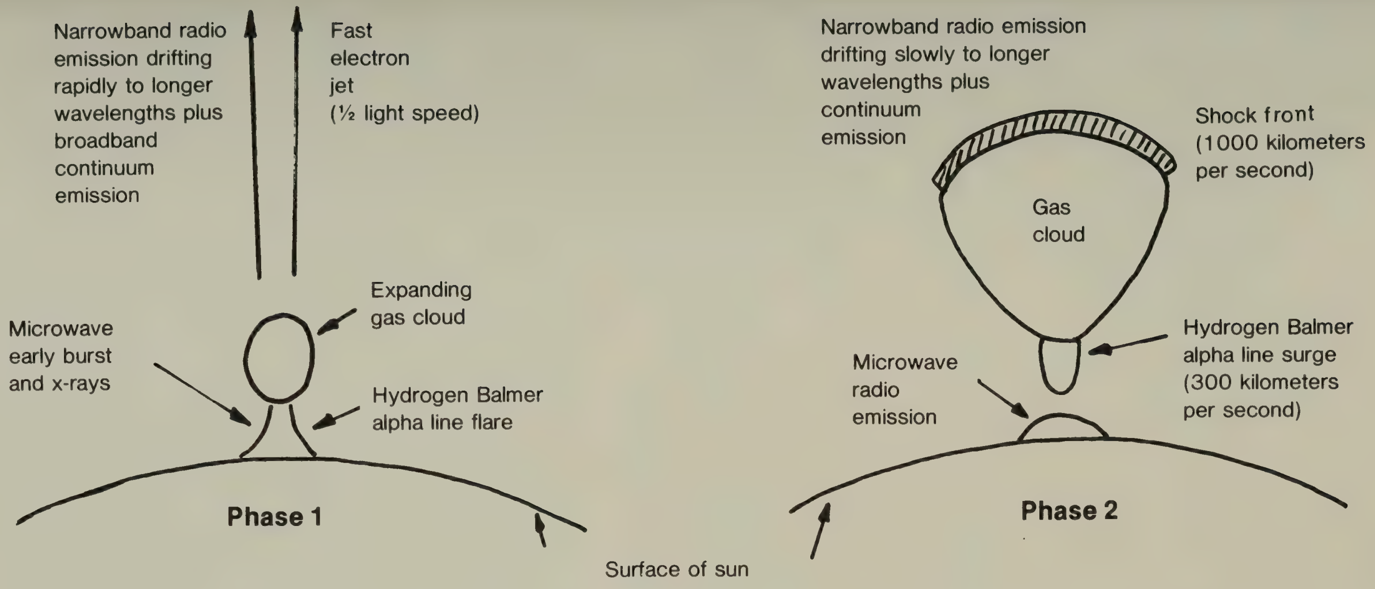
On March 1st, 1969, another great eruption occurred on the sun. The progress of this event was captured by a new 1.5 kilometer radio telescope at Culgoora, Australia, which produces radio pictures of the sun as shown in the accompanying set of four frames. The movement of a huge cloud of electrons and other particles ejected by the explosion of the sun is shown in the second, third and fourth frames at intervals of 52, 92, and 123 minutes after the first frame. In the second frame the cloud had traveled 1.5 million kilmoteres (one solar diameter). The third and fourth frames trace further progress of the cloud. In the third frame note that another explosion has just occurrred on the other side of the sun.

The sun is indicated by the white circle. The earth, 150 million kilometers away and far out of the picture, would be the size of one of the small dots of which the picture is made.

When the cloud, containing vast numbers of charged particles arrived at the earth like a solar gale a day or so later, it caused magnetic storms (disturbances in the earth's magnetic field which make compasses fluctuate) and also colorful auroral displays.

Such an explosion, or eruption, is the most violent event which occurs in the solar system, equal in intensity to the simultaneous explosion of millions of atomic bombs. Many such events may occur on the sun in a year.

Although the event of March 1, 1969, is not the same one as photographed by Joseph Klepesta they were probably similar. Comparing Klepesta's



Narrowband radio emission drifting rapidly to longer wavelengths plus broadband continuum emission
Fast electron jet (½ light speed)
Microwave early burst and x-rays
Expanding gas cloud
Hydrogen Balmer alpha line flare
Phase 1
Surface of sun
Narrowband radio emission drifting slowly to longer wavelengths plus continuum emission
Shock front (1000 kilometers per second)
Gas cloud
Hydrogen Balmer alpha line surge (300 kilometers per second)
Microwave radio emission
Phase 2

Phase 1 usually lasts only a few minutes and is then followed by Phase 2 that may last for hours or days.

Phases of a solar outburst (after J.P. Wild).

photographs with the Culgoora frames we note that the optical display at its maximum extent is less than a solar radius above the sun's surface. Completely invisible to the optical telescope is a cloud of electrons ejected much further. It is this cloud that is detected with a radio telescope. Thus, the radio telescope picks up the progress of an event where the optical telescope leaves off. In comparing Klepesta's photographs with the Culgoora frames one should note the change in scale, the photographs being a close up of the sun while the Culgoora pictures give a more distant view. Paul Wild of Australia, who built the Culgoora radio telescope, has divided the progress of a solar eruption or outburst into two phases. In phase 1, the visually observable flare appears with strong emission in the hydrogen Balmer alpha line (656 nanometers) accompanying the ejection of a huge electron jet at velocities approaching half the velocity of light but slowing down gradually as it gets further from the sun. During this phase x-rays and centimeter radio waves are observed from the region of the optical flare. Within less than a minute, as the electron jet moves upward, radio waves are detected at progressively longer wavelengths. The radio waves are believed due to the synchrotron emission of electrons spiraling outward in the sun's magnetic field.

In phase 2, a gas cloud comes up behind the electron jet but moves much more slowly. As it rises through the corona it generates radio waves at its leading edge as it pushes its way out through the solar corona.

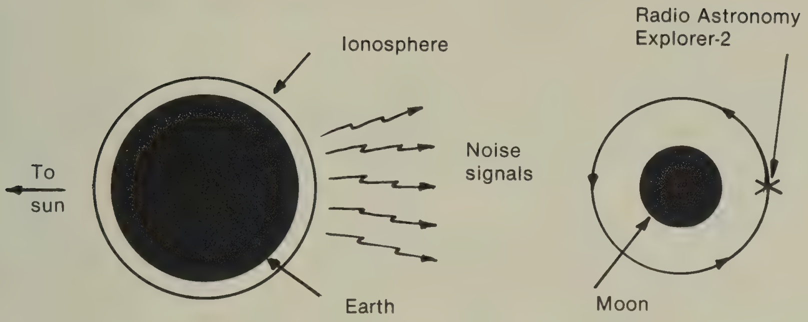
The Moon

The moon is our nearest neighbor in space. Although we call it a satellite of the earth, it is much larger relative to the earth than the other moons or satellites of the solar system are to their respective planets. The earth and moon can even be thought of as a double planet.

The moon is a large, lifeless, prosaic piece of rock but it makes a marvelous screen. For example, when the moon occults (moves in front of) a radio source an accurate timing of both its disappearance and reappearance yields a precise position for the radio source, because the moon's position is accurately known, while the manner in which the source fluctuates as it is cut off or reappears provides information about the source size or structure. This technique produced the most accurate source positions for some years before large aperture-synthesis interferometers were constructed. Its disadvantages are that it can be applied only to radio sources in the band of sky traversed by the moon and then only when an occultation occurs.

A Radio Telescope Behind the Moon

To escape from interference from earth-based transmitters, radio astronomers have long dreamed of a radio observatory on the back side of



Long wavelength radio observatory orbiting behind the moon for shielding from powerful naturally-produced radio noise signals from the earth.

the moon where it would be shielded from the earth. Although not fixed to the back side of the moon, the NASA Radio Astronomy Explorer — 2 satellite launched in June 1973, was put into orbit around the moon in order to take advantage of the moon as a shield from the earth, spending about half the time in the moon's shadow of the earth, an astronomer's dream being realized, at least in part. The satellite carries a 37 meter long dipole antenna, a V-shaped antenna 229 meters long and radio receivers for wavelengths between 33 and 1200 meters for observing the long wavelength background radiation from our galaxy.

The earth's ionosphere or charged particle sphere, several hundred kilometers above the earth's surface, is usually an effective barrier preventing wavelengths of 100 meters or more from reaching the earth. Grote Reber, the radio pioneer, has constructed a large dipole array in Tasmania which can "see through" the ionosphere at wavelengths as long as 300 meters on occasional nights when the electron density in the ionosphere drops to abnormally low values. But to observe at even greater wavelengths it is necessary to get above the ionosphere. It was for this reason that NASA put its equipment on a satellite and the lunar orbit was chosen to obtain shielding from long wavelength radio noise signals of enormous strength generated by electrons circulating in the particle belts above the earth's ionosphere (see page 13). On the night side of the earth these noise signals may reach powers of as much as one billion watts in the wavelength range of 1000 to 3000 meters. If these noise signals were to penetrate the ionosphere they would completely jam the radio broadcast transmissions in the European long wave band.

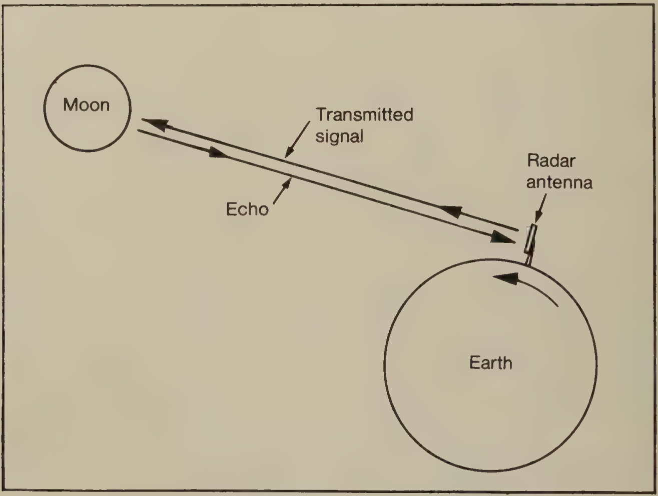
Diana Waves Back — The First Moon Bounce

"This is WSM," was an announcement familiar to millions of mid-continent Americans in the years prior to World War II. Radio was king; television was in the future and WSM, at Nashville, Tennessee, was one of the nation's most powerful clear-channel broadcasting stations.

The chief engineer of WSM was "Jack" DeWitt, a graduate of Vanderbilt University in Nashville. Although radio was Jack's first love, astronomy was his second and he had often wondered if it would be possible to beam a radio wave to the moon and receive an echo back. Perhaps . . — but it seemed like an impossible dream.

When World War II broke out, Jack left WSM and by 1943, at age 37, had become Lt. Colonel John H. DeWitt, Director of the Evans Signal Laboratory of the U.S. Army at Belmar, New Jersey, with responsibility for radar development.

Radar is an acronym. It stands for **RA**dio **D**irection **A**nd **R**ange. It is also a palindrome (spelled the same forwards and backwards). Developed during the war, radar can "see" in the dark and through clouds and fog. Its principle is as simple as clapping your hands in a canyon, a large room or in a cave. The clap sends out a sound wave and the walls reflect back an echo. The further away the walls, the longer the wait or delay for the echo. In-



At moonrise, the earth's rotation makes the radar antenna approach the moon at 1200 kilometers per hour.

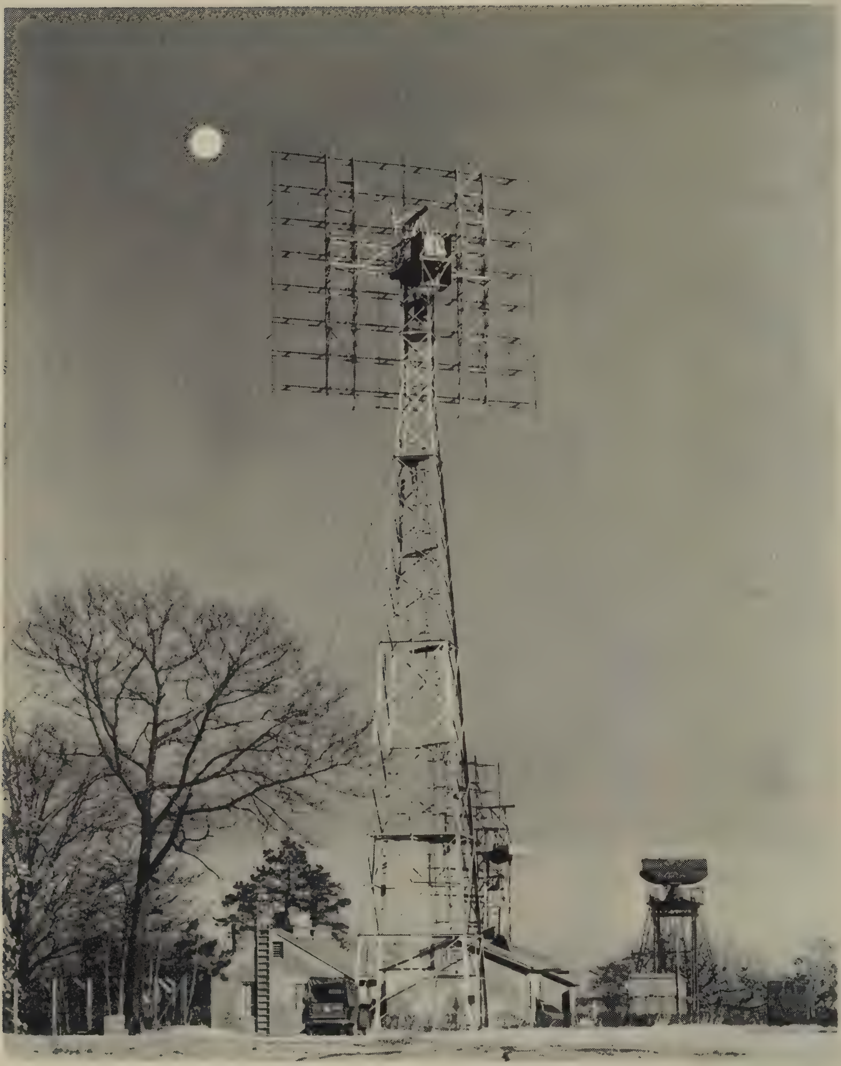
stead of a clap of sound waves, a radar sends out a pulse of radio waves from an antenna. A receiver then listens for echoes bouncing back from some object or objects in the path of the radar's beam. The echo delay time is a measure of the distance or range of the object. Turning the antenna for maximum echo response gives the direction of the object. In practice a succession of pulses are transmitted with listening done in the intervals between.

Although moon echoes may have crossed Jack's mind during the war, there was urgent business at hand. At the war's end in August 1945, however, priorities changed and Jack had his chance. With some other engineers at the Evans Laboratory, he organized Project Diana, named after the goddess of the moon, with the intent of trying a moon bounce.

The moon was larger than any object previously detected by radar but it was also much farther away. The average distance of the moon is about 380 000 kilometers so the time for a radio signal to reach the moon is about 1¼ seconds and the time for the return is another 1¼ seconds. Thus, the expected echo should arrive back 2½ seconds after a pulse was transmitted.

Jack and his group began to assemble components from many different radars. They had calculated that only a very special combination of equipment would do the job. The transmitter they chose was a 3 kilowatt unit while the receiver was a very sensitive type. The wavelength of 2.7 meters, which they selected, was short enough, they believed, to penetrate the ionosphere or charged particle layer surrounding the earth above the atmosphere.

The Diana team at the Evans Signal Laboratory, January 1946. From the left, Jacob Mofenson, Harold D. Webb, Lt. Col. John H. DeWitt, Jr., E, King Stodola and Herbert Kaufman.



Moon radar at Evans Signal Laboratory.

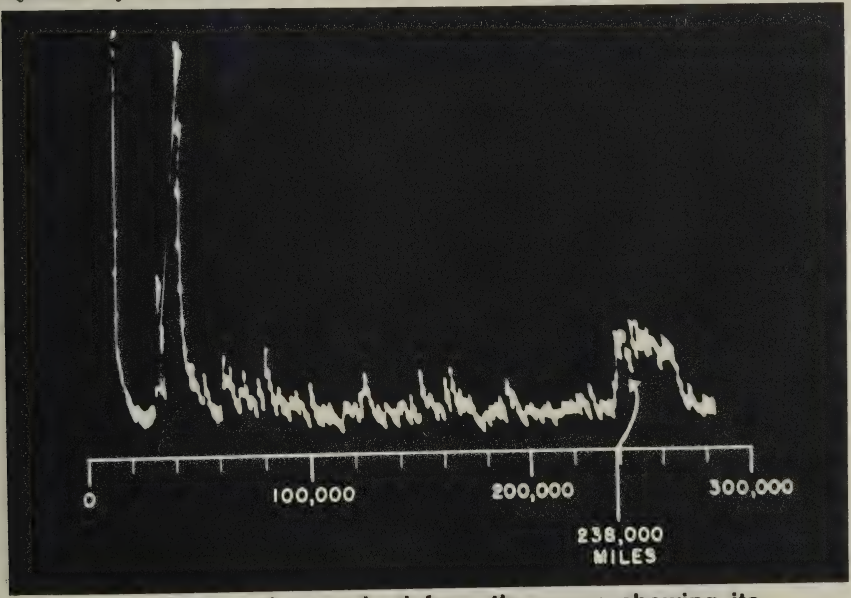
For the antenna they combined two Army SCR-270 radar antennas making a "billboard" array of 64 half-wavelength dipoles measuring 12 by 12 meters and mounted it on a 30 meter tower at the edge of a bluff overlooking the Atlantic Ocean near the Shark River inlet on the Evans Laboratory grounds. This array should increase the power radiated toward the moon by a factor of 64 giving the same effect as 192 kilowatts in a single dipole. They connected a switch to the antenna so that after a pulse had been sent, it could be thrown to connect the antenna to the receiver.

For weeks Jack and his group sent pulses and listened but there was no echo. They did not listen at the same wavelength as they transmitted because at moonrise they were approaching the moon by as much as 1200 kilometers per hour due to the earth's rotation. Therefore, they tuned the receiver to a somewhat higher frequency to compensate for the doppler shift.

They were plagued with equipment troubles but finally about noon on Thursday the tenth of January, 1946, as the moon was rising over the Atlantic, they detected their first echo! They heard it 2½ seconds after the transmitted pulse and it showed up as a distinct bump or "pip" on a cathode-ray tube screen. After a few seconds they sent another pulse. Two and one-half seconds later its echo came back. More pulses, more echoes. There was cheering and backslapping but word of their success did not reach the public until in March when Jack announced it at a National Convention of the *Institute of Radio Engineers* in New York City.

For the first time mankind had sent something of its own making to another celestial body and received it back. Man had reached out with radio waves and Diana had waved back. Twenty-three years later man would leave his footprints. No longer could the goddess Diana or the rest of the cosmos remain aloof to mankind.

Project Diana marked the beginning of the exploration of the solar system by radar and of also inadvertently perhaps informing any in-



Radar echo received from the moon showing its range as 238,000 miles.

telligent creatures beyond of our presence since the strong beams of radars have the best chance of traveling furthest.

But radar has its limitations as can be realized from a consideration of the time delays involved. The moon is 1¼ seconds wave travel time distant (1¼ light-seconds) so the echo time is 2½ seconds. Depending on its position in its orbit, Mars is 3 to 21 minutes wave travel time distant (3 to 21 light-minutes) so echoes may take 6 to 42 minutes. Pluto, the most distant planet in the solar system, is 5½ hours wave travel time distant (5½ light-hours) and an echo would take 11 hours. Although radar echoes have been received from Mars, Pluto is yet a bit beyond the capability of presently available equipment.

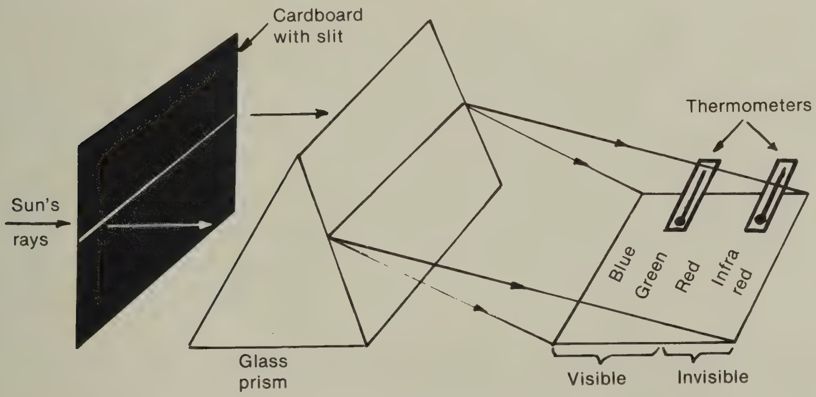
But consider the problem of obtaining a radar echo from the nearest stars at distances of 4 light-years or more. The echo time delay is 8 years, but worse, a transmitter would be required with a power of 10 000 million million times that of a Mars radar!

Thus, earth-based radar exploration beyond the solar system is far beyond our present technology, but it is not beyond thinking and planning. Thus, a Project Cyclops antenna, proposed for a search for extraterrestrial intelligent signals, might do the job (see page 218).

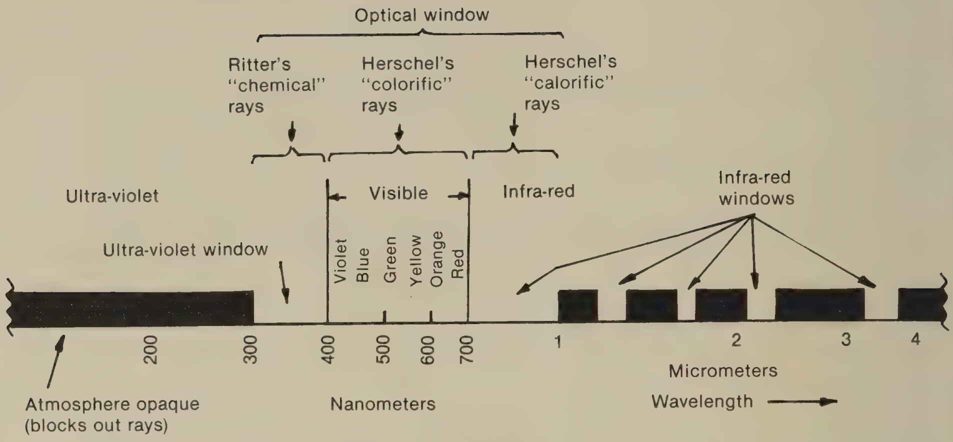
OTHER ASTRONOMIES

Herschel and Infra-red Rays

William Herschel, the musician turned astronomer, was the discoverer of infra-red radiation. He had tried glasses of various colors to darken the sun while observing it with his telescopes and found that although red glasses reduced the light effectively they allowed heating of the eye with attendant irritation. He found that dark green glasses or smoked glasses worked much better, reducing both the light and heat. To learn more about the heating and illuminating power of the sun's rays he contrived an experiment. Using a prism to spread out the sun's light into its spectrum or colors he placed a thermometer successively in the regions of different colors. He noted that the thermometer reading was lowest when in the violet region, higher in the green and even higher in the red. He discovered further that if the thermometer was moved just out of the red end of the spectrum so that it was not illuminated by the sun's light, its temperature went still higher. There were obviously invisible rays carrying the heat, rays which were refracted by the prism and akin to light.



Herschel's experiment. He found that the thermometer in the invisible part of the spectrum beyond the red gave a higher temperature than the one in the visible part of the spectrum.



The visible spectrum and the optical spectrum between the ultra-violet and infra-red The atmosphere blocks out or is opaque to ultra-violet radiation less than 300 nanometers and to most infra-red radiation longer than 1000 nanometers. See complete electromagnetic spectrum on page 42.

The limits of 300 and 1000 nanometers for the optical spectrum are somewhat arbitrar and have been rounded off for convenience; actually the long wavelength limit is more lik 1100 nanometers. The nominal 400 and 700 nanometer values for the visual spectrum ar also somewhat arbitrary; some authorities would place the long wavelength limit at 75 nanometers. In any case, the cut-off at the limits is not knife-edge sharp but rathe gradual.

In a series of papers before the Royal Society in London in 1800, Herschel reported on his experiments and called "these invisible rays which produce no illumination but create a sensation of heat, *calorific rays* or *radiant heat.*"

To describe the light rays which produce visible illumination but little heat he used the contrasting term "*colorific rays.*" In further experiments Herschel found that the maximum illumination occurred in the yellow-green region in the middle of the "colorific" spectrum (550 nanometers). For *calorific* and *colorific* rays we now use the terms *infra-red* and *visible rays.*

A pavement or brick wall baked by a late afternoon sun can, in the darkness of evening, warm one's body from a distance of many feet. The heat is conveyed by invisible infra-red rays. Our skin is sensitive to infra-red rays but not to light unaccompanied by heat or infra-red rays. Conversely, our eyes are sensitive to visible light but hardly at all to infra-red rays.

If our eyes were sensitive to infra-red waves instead of light a warm room would appear brighter than a cold one and the inside of a refrigerator would be very dark indeed. A person wearing a white shirt and black pants would appear to have a dark shirt and bright pants. At some infra-red wavelengths (10 micrometers) the sky would appear bright by both day and night while at other wavelengths (2 micrometers) it would appear dark.

At wavelengths greater than 1 micrometer where photographic films or plates are insensitive to infra-red rays,thermaldetection devices may be used Typically, all of the incoming radiation collected by a telescope mirror is focused on a cell whose electrical resistance depends on the infra-red radiation. The changes in resistance can be measured and recorded. In this way infra-red stars and other celestial hot spots can be located. A common form of cell for infra-red waves uses germanium with traces of gallium. To perform properly the cell is refrigerated to within a degree or two of absolute zero. This type of infra-red detector was invented by Frank Low in 1960 while he was employed by the Texas Instrument Company in Dallas.

Ritter and Ultra-violet Rays

In 1801, only a year after Herschel had discovered invisible heat rays beyond the red end of the visible spectrum, John Wilhelm Ritter of Silesia found that invisible rays from the sun beyond the violet induced changes in chemical compounds. Accordingly, these rays were called ''chemical'' rays. We now use the term ''ultra-violet.'' These rays can be readily detected with photographic film.

Although our eyes are not sensitive to the ultra-violet rays from the sun (between 300 and 400 nanometers), our skin reacts to them by acquiring a tan. It is fortunate that the atmosphere is opaque to ultra-violet rays shorter than about 300 nanometers. If these even more chemically active rays were to penetrate to the earth's surface they would produce biological and ecological effects which could upset the environmental balance. The blocking of rays just short of 300 nanometers is due to absorption by the ozone of the upper atmosphere. The ozone molecules, consisting of three oxygen atoms, are formed from the normal two-atom molecules of oxygen by the ultra-violet rays of the sun.

Mountain climbers at high altitudes quickly acquire a shallow tan from the sun. This results from shorter ultra-violet waves than can reach sea level. The shallow, high-altitude tan doesn't last long. At sea level the tan is due to the longer ultra-violet waves which penetrate the skin more deeply and impart a longer-lasting tan.

Ultra-violet and Infra-red Astronomies

Wavelengths less than 400 nanometers are termed *ultra-violet* and those longer than 700 nanometers, *infra-red.* For infra-red wavelengths of 700 to 1100 nanometers photographic techniques with infra-red sensitive film can be used. Wavelengths longer than 1000 nanometers (1 micrometer) require special techniques and for wavelengths as long as 1000 micrometers (1 millimeter) the infra-red blends into the short wavelengths of the radio part of the spectrum. At the short wavelength end of the ultra-violet region (10 nanometers) the ultra-violet blends into the long wavelengths of the x-ray part of the spectrum.

Infra-red radiation from the sky penetrates the atmosphere in the 700 to 1000 nanometer region and through several narrow windows in the 1 to 35 micrometer region. Ground based observations can be made at these wavelengths but for longer wavelengths to the shortest radio wavelengths of about 1000 micrometers (1 millimeter) the atmosphere is very opaque and observations are best made from above the atmosphere.

Many astronomical objects have been found to radiate more strongly in the infra-red than expected. Many such objects emit most of their energy at infra-red wavelengths and some bright infra-red sources or super-red stars are undetectable at any other wavelengths. Other objects, such as some powerful, distant quasars, and some spiral galaxies, radiate strongly in the ultra-violet.

What can be said about the evolution and age of a star? For example, is the sun young or old? This is not an easy question to answer because stars live for billions of years and our knowledge of them is very brief. Nevertheless, a theory of the evolution of stars has been developed.

At one time the term *nebula* was used to describe all diffuse appearing objects including galaxies which we now know to be distant aggregations of millions of stars. Although it is no longer customary to refer to galaxies as nebulas, the term nebula is used to describe many other diffuse cloud-like objects such as the Orion nebula. This nebula and others like it consist of clouds of gas and dust and tend to be found near the plane of our galaxy.

They are like an interstellar smog, and appear to be the breeding place of new stars. The dust particles consist typically of a mixture of silicon compounds, graphite (a form of carbon) and ices and are typically about 100 nanometers in size. They are big enough to impede blue light but less effective at impeding the longer wavelengths of red light or infra-red radiation. For the same reason, dust particles in the earth's atmosphere cause the setting sun to appear red.

Since red light and infra-red radiation can penetrate these nebular dust clouds, these waves can inform us about conditions inside. A number of very strong infra-red sources discovered in some large clouds appear to be stars in their earliest stages of formation, condensing out of the cloud particles and heating up gradually as the cloud collapses under gravitational attraction.

As contraction continues, the star at the core of the cloud may eventually reach a temperature of 10 million degrees (kelvin) which is high enough for

The Orion nebula, a birthplace of stars. The hydrogen gas of this nebula is ionized by ultra-violet radiation from hot stars and emits a thermal radiation which is strong at infra-red and short radio wavelengths. Within the cloud are dense regions which are slowly heating up as they collapse into stars. The visible cloud, several light-years in diameter, is part of a much larger gas and dust region containing many different kinds of elements and molecules. (Courtesy of K. Aa. Strand).

hydrogen burning, or the fusion of hydrogen to helium, to begin. The heat of fusion produces an outward radiative force that counter balances the inward gravitational attraction. It takes 50 to 100 million years for a star like the sun to reach this stage. Then, with inward and outward forces eventually reaching equilibrium, contraction stops and the star reaches the "main-sequence" stage and settles down to a long stable period — many billions of years. This may be inferred from the fact that there are so many stars in the "main sequence" region and so few elsewhere on the power-temperature diagram (see page 53). Stars don't stay long in the more empty regions of the diagram.

During the long stable period as a main-sequence star, the star's mass decreases very gradually as mass is converted into energy and radiated away mainly as light and heat (infra-red radiation) and to a lesser extent in radiation of other wavelengths.

The sun has probably been a main sequence star for several billion years and is probably good for a few billion more. Thus, the sun is neither young nor old but more like middle-aged, perhaps a bit past it.

Infra-red observations reveal the *cool* stars while *ultra-violet* observations disclose the *hot* ones. A star at birth, condensing out of a gas and dust cloud, radiates most at infra-red wavelengths. As it contracts further it heats up and emits more strongly at visible wavelengths. After further evolutionary changes, the star may become even hotter and radiate most strongly in the ultra-violet. These hot stars spew out material in interstellar winds or by more explosive means, forming gas and dust clouds from which, in turn, new stars may eventually condense and form. Thus, the presence of young stars may be inferred from *either* infra-red or ultra-violet radiation.

Since the earth's atmosphere is opaque to wavelengths shorter than about 300 nanometers, it is necessary to make ultra-violet observations at wavelengths shorter than this from satellites or probes above the atmosphere. Other than for this requirement there is little difference between ultra-violet astronomy and the older, more traditional earth-based optical astronomy.

From observations by Orbiting Astronomical Observatories, such as OAO-II launched in 1968, much information has been obtained about the ultra-violet shortward of 300 nanometers. Photocell devices sensitive to ultra-violet radiation revealed a solar spectrum rich in emission lines dominated by emission from hydrogen as short as 30 nanometers and for the first time the spectra of hot stars were traced into the ultra-violet where the maximum radiation may occur.

The Copernicus satellite (OAO-III) and the International Ultra-violet Explorer (IUE) satellite have provided much information on the various elements and their abundance in the interstellar medium. Not only hydrogen, but other elements are present including carbon and iron and results indicate that there is a tendency for some of the elements to be swept up and deposited on the dust particles of the interstellar medium.

Ultra-violet observations are vital to an understanding of galaxies because they permit studies of the hot stars of the galaxy. Galaxies which look alike optically may be very different at ultra-violet wavelengths because one hot ultra-violet star may radiate as much power at 150 nanometers as a million red giant stars. Thus, the number of these hot ultra-violet stars in a galaxy makes a marked difference in the total power output of a galaxy, and a galaxy which is emitting strongly in the ultra-violet is probably one where star formation is going on.

Maffei 1 and 2

In 1968, Paolo Maffei, of the Asiago Observatory in Italy, took some photographs with special infra-red sensitive plates of a region of sky along the galactic plane. He noted two unusually prominent infra-red objects which were hardly visible on optical photographs. His article about them attracted the attention of other astronomers who found by additional observations, both infra-red and radio, that these objects are the dense nuclei of two large nearby galaxies. They are almost totally obscured optically because they lie in the plane of our galaxy and are nearly blocked from view by the intervening dust. These galaxies, now known as Maffei 1 and 2, are newly recognized members of our *galactic neighborhood.* (See The Galactic Neighborhood in the Universe in Seven Steps on page 18).

X-rays — From Roentgen to UHURU

On a Friday afternoon of November 1895, Wilhelm Roengten was testing a discharge tube in a laboratory room of the Physics Building of the University of Wurzburg, Germany. The tube, about the size of a liter bottle, was made of glass and most of the air had been pumped out. A metal plate inside each end of the tube was connected by wires through the glass to a high-voltage spark coil. When the coil was turned on, a bright discharge or glow occurred inside the tube due to electrons passing between the metal plates. The electrons did not penetrate the glass but if such a tube were fitted with a very thin metal "window" the electrons could pass through into the air and travel for a few centimeters. The electrons were readily detected by the fluorescence or glow they produced when a piece of cardboard painted with a barium compound was held near the window.

Roentgen's "bottle," called a Hittorf-Crookes tube, which he had chosen for today's experiment had no windows. It was all glass. Roentgen, a 50 year old physics professor, had wondered if some fluorescence might nevertheless be detectable. He had prepared a small cardboard with barium paint to test for it. He reasoned that the fluorescence might be very weak so he pulled the shades to darken the room and had completely enclosed the tube in a black cardboard box to shield his eyes from the glow of the tube.

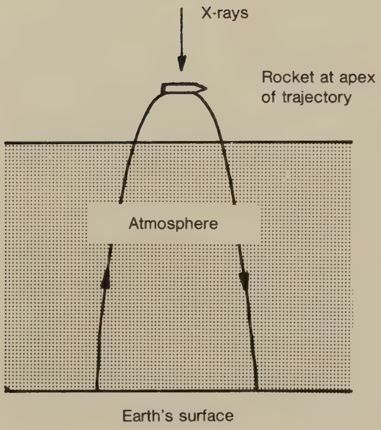
He groped in the dark for the switch and turned on the Ruhmkorff spark coil. He heard the buzz of the Deprez interrupter and the hiss of the high voltage but saw no light from the tube through the cardboard cover. He was satisfied with the arrangement.

He was about to turn off the coil when his eye caught a faint glimmer from a table next to the one with the discharge tube. Perhaps it was a mirror or shiny piece of metal reflecting a spark from the high voltage coil, he thought, but this seemed unlikely. When he turned off the coil the glow was gone but it appeared again each time he turned on the tube. Roentgen was puzzled. He lit a match to see what might be producing the glow and there, to his amazement, was his small barium-painted piece of cardboard. How could this be? He moved the cardboard further away and when he turned on the tube it glowed again. He was struck with the realization that something must be emanating from the tube! It could not be electrons because even if they did escape the tube they could only travel a few centimeters through the air. His cardboard glowed a full two meters away. This was a hundred times further than electrons were known to penetrate!

Entranced, Roentgen made further experiments on the strange radiation. That evening he was late for supper — Wilhelm Conrad Roentgen had discovered a new kind of ray he called the x-ray.

What is an x-ray? It is an electromagnetic wave like light but of much shorter wavelength. In fact, the wavelength of an x-ray is so short that it is less than the spacing between the atoms of solid matter enabling the rays to travel through materials like light waves pass through the holes of a window screen.

Now, nearly a century after Roentgen's discovery, x-ray telescopes ride earth satellites high above the earth's atmosphere recording x-rays from distant celestial sources enormously more powerful than Roentgen's tube in the cardboard box.



Rocket above atmosphere detects cosmic x-rays.

But until 1950 no one knew if celestial objects emitted x-rays because the earth's atmosphere is opaque to x-rays. Then, an x-ray detector carried above most of the atmosphere by a small rocket sent up by the Naval Research Laboratory found x-rays from the sun.

Later, in 1962, another Aerobee rocket instrumented by the American Science and Engineering Co. was launched at midnight from White Sands, New Mexico, to search for x-rays from sources other than the sun. The rocket attained an altitude of 230 kilometers and for over 5 minutes was above most of the atmosphere. Geiger counters on the rocket recorded x-rays of unexpected intensity from a localized region of the sky. If this radiation came from a nearby star it meant that the star must have an emission rate for x-rays at least 10 million times greater than for the sun! Subsequent rocket flights of x-ray equipment established that the radiation was coming from a source in the constellation Scorpio near the galactic center. The new object was given the designation Sco X-1.

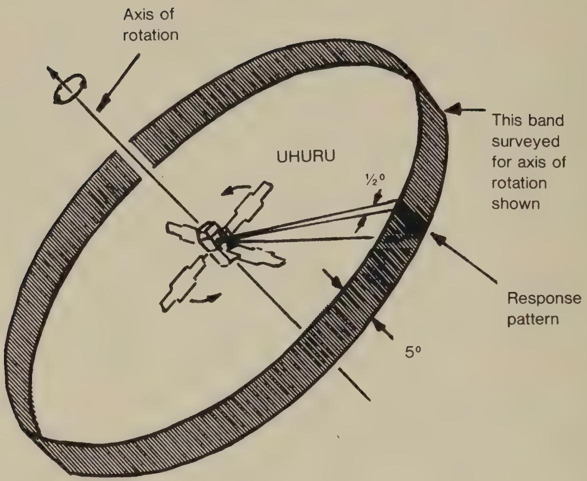
A rocket flight in March 1966 gave a sufficiently accurate position for Sco X-1 that Minoru Oda of the Tokyo Observatory was able to associate Sco X-1 with a faint (13th magnitude) blue star. The star was found to be variable and emitted 1000 times more power in x-rays than in light! It was a new and puzzling kind of object.

In 1963 NASA gave support to plans for an x-ray explorer satellite. Seven years later the completed satellite was mounted on a Scout booster and launched by the Italian Air Force from a platform floating in the Indian ocean 5 kilometers off the coast of Kenya on December 12, 1970. This date marked the 7th anniversary of the independence of Kenya. General Broglio, the launch facility commander, proposed that the satellite be named UHURU (oo-hoo-roo) to commemorate Kenya's independence, "Uhuru" being the Swahili word for "freedom." The Kenya launch site, a few degrees south of the equator, had been chosen to achieve a nearly equatorial orbit.

With UHURU in orbit, x-ray astronomy moved from a few sporadic fleeting cosmic glimpses a year, only as long as a rocket was at the apex of its trajectory, to a full-time, full-sky astronomy as UHURU orbited the earth spinning leisurely while its x-ray counters systematically scanned the heavens.

Soon UHURU began radioing its findings back to earth and many new x-ray sources began to emerge from the data. Man now had x-ray eyes to probe the cosmos.

Within a year UHURU had discovered over a hundred x-ray sources but only a few could be identified with known optical or radio objects. The situation was reminiscent of radio astronomy two decades earlier when only a few radio sources could be identified with optical objects. However, one x-ray source was identified with the pulsar at the center of the Crab nebula.



UHURU's x-ray detector response pattern (½° x 5°) scans once around the sky as UHURU rotates 5 times per hour. By torquing UHURU's axis of rotation slightly around another band or zone of sky is scanned. In this way the entire sky was surveyed for x-ray sources.

This remarkable spinning object blinks off and on 30 times per second at x-ray, gamma-ray, light and radio wavelengths!

While UHURU was continuing its observations more x-ray satellites went into orbit resulting in more sources, better positions and more identifications.

X-ray sources seem to be at least of three kinds:

(1) *Pulsars* such as the one in the Crab nebula. X-rays from the Crab nebula come partly from the gaseous envelope (in the supernova remnant) and partly from the spinning pulsar at its center.

(2) *Supernova remnants* such as Cassiopeia A. In such a remnant the rapid expansion of the hot gas shell into the interstellar medium may produce x-rays at the shock front where fast electrons in the shell encounter the surrounding medium in the same way that x-rays are produced in an x-ray tube when high speed electrons are suddenly stopped when they hit a metal plate (as in Roentgen's x-ray tube), the electron energy being converted into electromagnetic radiation of very short wavelength (x-rays).

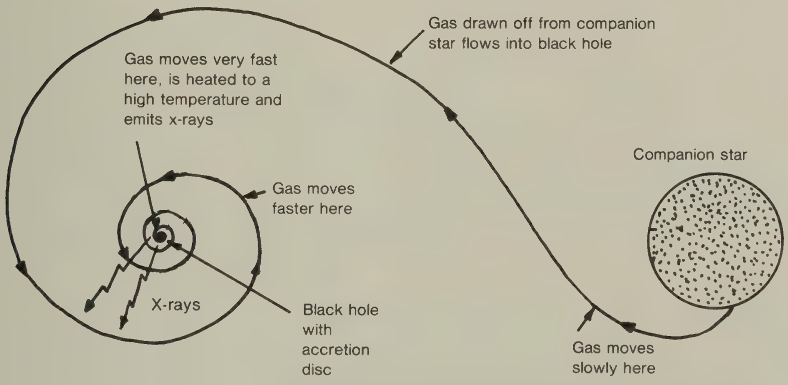
(3) Binary or *double star systems* involving an ordinary star and either a neutron star or a black hole. The x-ray source Cygnus X-1 is thought to be an example of a system with a black hole.

Double stars are quite common, the two stars revolving around each other. If the nuclear heating ceases in one of the stars it may collapse under its own gravity into a *neutron star,* or, if the star is more massive, collapse further into a *black hole.* The collapsed highly-compact object will gradually draw off gaseous material from its normal companion as it continues to circle it. The details of what happens are not clear but may be somewhat as follows. As the material is sucked into the black hole, under the influence of its enormously strong gravitational field, electrons will be accelerated to nearly light speed, radiating x-rays as they encounter other particles not moving as fast due to irregularities in the flow.

A black hole is so dense (like the earth crushed to the size of a pea) and has such a strong gravitational field that no x-rays, light or other radiation can escape. It is therefore invisible. However, the gravitational field or region of gravitational attraction around it holds its companion star in orbit around it.

Optical astronomy revealed the stars, planets and galaxies. Through radio astronomy quasars and pulsars were added to the celestial showcase. Now with x-ray astronomy the amazing black holes take their place.

Many x-ray objects fluctuate rapidly in intensity. X-ray sources have also been discovered which produce bursts of radiation in pulses of approximately 10 seconds duration. The bursts may be repeated but not necessari-


Gas drawn off from companion star flows into black hole
Gas moves very fast here, is heated to a high temperature and emits x-rays
Companion star
Gas moves faster here
X-rays
Black hole with accretion disc
Gas moves slowly here

A black hole pulls in gas from its companion star and gives out x-rays.

ly in a regular periodic manner. However, in one case a series of several hundred bursts was detected at a nearly uniform interval between bursts of 84 minutes.

If an astronaut's eyes were sensitive to x-rays he would see a cosmos filled with the twinkling lights of a Times Square or the Strip at Las Vegas. These fluctuations are inherent in the source and are not due, for example, to the solar wind (quasar scintillation). The material which a black hole strips from its companion star may come in chunks and bunches instead of in a smooth uniform flow, thus, producing rapid fluctuations and bursts of radiation, by crude analogy like the bursts of noise from a kitchen sink dispose-all, the household "black hole," when it encounters stubborn bits of garbage.

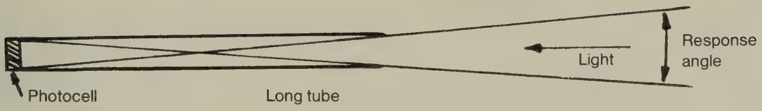
The first devices for detecting extraterrestrial x-rays could hardly be called telescopes because they were merely simple detectors which had no means of focusing. They accepted x-rays over a wide angle in the same way that the emulsion of a photographic plate placed on a table is sensitive to light falling on it from a wide range of angles.

To obtain a directional indication without focusing, the rays can be collimated by slats or tubes in the same way that a photocell at one end of long tube, blackened inside and devoid of lenses, will be responsive to light coming from within a restricted angle into the open end. The angular resolution is obtained, however, at the expense of low sensitivity. Some x-ray detectors use this principle with a Geiger counter or scintillation counter in place of the photocell. Such collimation devices were used for angular resolution on UHURU.

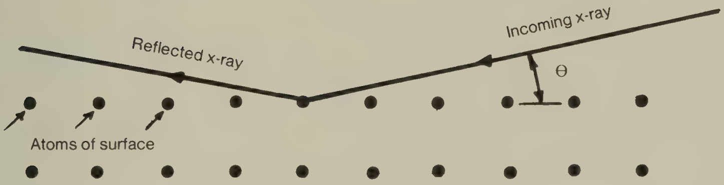
The focusing of x-rays poses a problem because x-rays will pass right through an ordinary mirror with very little scattered back to a focus by the atoms of the mirror surface. However, at nearly grazing incidence the atoms present a more continuous surface and if the rays impinge at less than a critical angle they will be totally reflected.

In 1960 Riccardo Giaconni and Bruno Rossi proposed a variety of focusing x-ray telescopes based on this principle of total reflection. A simple example involves using only that part of a parabola where the rays impinge at less than the critical angle. X-ray telescopes with grazing incidence mirrors in various combinations have been constructed and flown on a number of satellites.

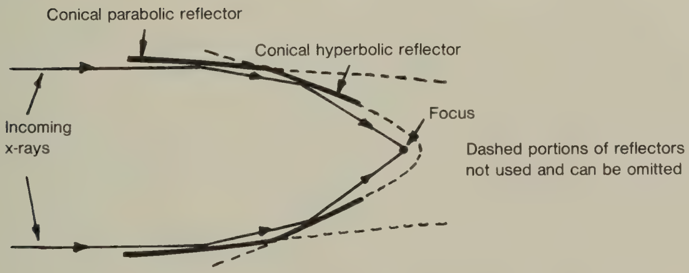
Since x-rays are so short one might expect high resolution from even small x-ray devices. However, the problems described above have limited the resolution of x-ray telescopes to something like 4 seconds of arc for the Einstein x-ray observatory orbited by NASA 8 years after UHURU.



A long tube will collimate waves and provide a directional effect without any focusing.



If x-rays impinge on the atoms of a surface at a small enough (grazing) angle Θ:, they will be totally (externally) reflected.


Conical parabolic reflector
Conical hyperbolic reflector
Focus
Incoming
x-rays
Dashed portions of reflectors
not used and can be omitted

How x-rays reflected at grazing angles from parts of a parabolic-hyperbolic mirror are brought to a focus. Only part of the telescope aperture is used so the collecting area is less than for a typical optical telescope of the same diameter.

Outburst from Cygnus X-3

When the Crab supernova explosion was seen in 1054 A.D. there were no radio telescopes so we don't know whether there was a radio outburst at the time. However, in 1972 a radio outburst was detected from an object which has no visible counterpart. On September 2nd, 1972, Philip Gregory of the University of Toronto turned the big 46-meter Algonquin Park, Canada, radio telescope to a radio source in the constellation of Cygnus. The source had originally been discovered during an x-ray scan from a rocket in 1966 and named Cygnus X-3. Later it was found to be emitting radio waves and also gamma-rays.

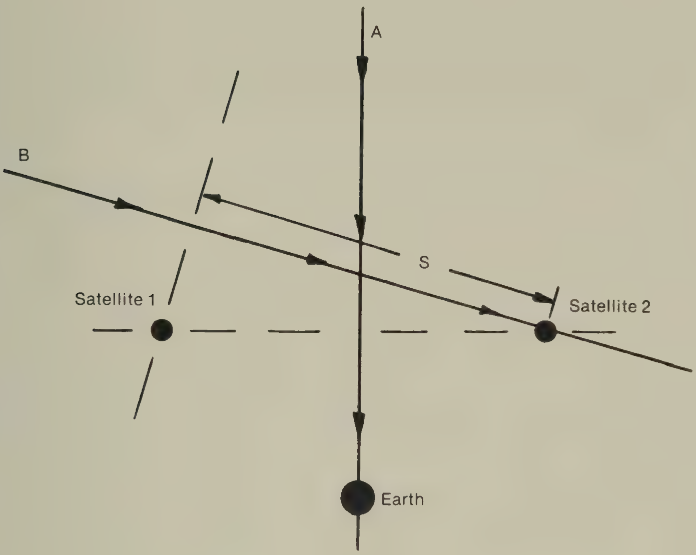
Gregory was amazed to find the radio emission a hundred times stronger than normal. Could this really be? He telephoned the Green Bank, West Virginia, radio observatory and astronomers there quickly confirmed that Cygnus X-3 was undergoing a spectacular outburst. Radio observatories around the world were alerted and the source was monitored at many wavelengths as the intensity gradually ebbed over the succeeding weeks. Curiously no change was noted in the x-ray strengths nor was anything visible detected.

Gamma-Rays from Space

The scientists were puzzled. Before them was evidence of a clandestine nuclear explosion in space but who was responsible? Telephone lines crackled but no news media carried the story; it was kept secret. Thus began the exploration of space with gamma-ray telescopes.

It was midsummer 1967. Not long before, the U.S. had orbited several satellites code-named Vela to monitor the Nuclear Test Ban Treaty. Aboard each Vela satellite was a gamma-ray detector. On July second the detectors on two of the satellites had recorded a short, intense burst of gamma rays, characteristic in many ways of the gamma radiation from a hydrogen bomb detonated in space.

If the time at which the burst was detected at each satellite were known accurately enough, it should be possible to determine a direction from the time differences. However, the timing accuracy as of 1967 was inadequate. Two years later, almost to the day, another burst was recorded. This time the timing was more accurate and the scientists at the Los Alamos laboratory were able to deduce a direction.



A burst of gamma rays from the direction *A* will arrive at the two satellites (1 and 2) simultaneously. However, a burst from the direction *B* will arrive at satellite 1 before it arrives at satellite 2. The difference in time of arrival is equal to the distance *S* divided by the velocity of the ray (300 000 kilometers per second). Thus, if *S* is 100 000 kilometers, the time difference is ⅓ second. With only two satellites there are ambiguities as to the direction of arrival but with more satellites these ambiguities may be resolved.

As time passed more burst events were detected at the rate of several per year. Although each seemed to come from a different place in the sky an important conclusion was reached. The earth, moon and other objects of the solar system could be ruled out; the outbursts were coming from beyond the solar system. Man was not responsible so the puzzle became scientific instead of political and the discovery was publicly announced. But the origin of these bursts remains an enigma.

What is a gamma-ray? The dividing line between gamma and x-rays is arbitrary. Actually gamma rays and x-rays tend to overlap or blend into each other, there being no real distinction between a short wavelength (hard) x-ray and a long wavelength (soft) gamma ray. The Vela satellite bursts have been in the long wavelength (soft) gamma ray region of the spectrum.

Later orbiting gamma-ray detectors have surveyed most of the sky. Its appearance is somewhat reminiscent of the radio sky in that there is a distinct band of emission from our own galaxy which lies close to the galactic plane. Its greatest strength is in the general direction of the center of the galaxy. There is also a weaker, diffuse background of gamma radiation from the entire sky which may be extragalactic in origin, that is, from beyond our galaxy.

Gamma-Ray Telescopes

A gamma-ray telescope may consist of a sandwich of cesium-iodide and sodium-iodide crystals and a nearby block of plastic. An incoming gamma-ray impinging on a nucleus of one of the sandwich atoms produces an electron-positron pair. The creation of the pair is accompanied by a pulse of light and this is detected by a photo-electric device. The electron-positron pair travels forward in the same direction as the incoming gamma-ray and the pair in turn can be detected by the Cerenkov light produced on entering a plastic block adjacent to the sandwich. When both sandwich and block light-monitors give a simultaneous indication, it signals that a gamma-ray has entered the ''telescope'' from the forward direction (sandwich to block). Gamma-rays coming from other directions may cause a sandwich indication but none in the block because the block is not in the path of the electron-positron pair. Thus, the sandwich-block combination has the ability to determine the direction of arrival of gamma rays.

The 21 centimeter line of the radio spectrum is produced by small energy transitions of hydrogen atoms. At the other end of the electromagnetic spectrum are gamma-ray lines resulting from the very much higher energy jumps within atomic nuclei and also by other processes.

For example, the annihilation of an electron by a positron produces gamma-ray line radiation at a wavelength of 2.4 picometers (photon energy 511 000 electron volts). A gamma-ray line at a wavelength of 976 femtometers, corresponding to a photon energy of 1.27 million electron-volts, results from a transition in the nucleus of an isotope of neon called neon-22, while another line results from the capture of a neutron by a proton to form a heavy hydrogen nucleus. As a further example, electrons moving in the intense magnetic field of a neutron star or pulsar radiate a gamma-ray line at a wavelength which depends on the strength of the magnetic field.

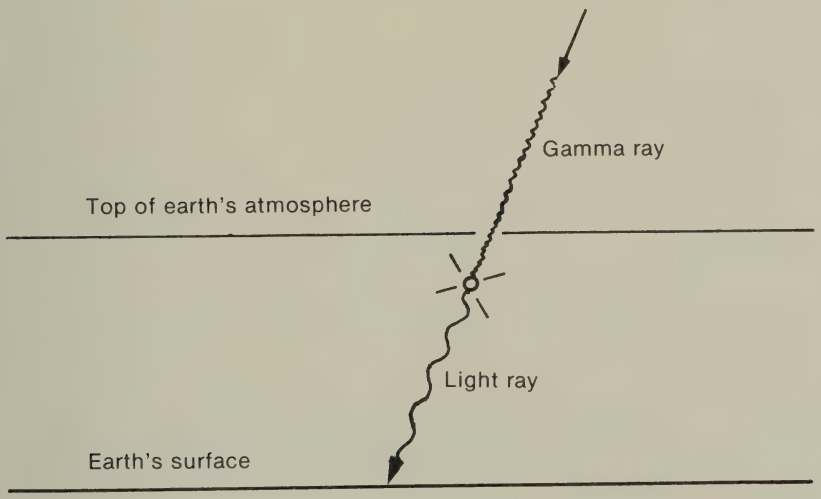
Some gamma-ray telescopes are now equipped with spectrum analyzers for the detection of these lines, informing astronomers about the presence of particles and nuclei in celestial objects as well as about the magnetic fields of neutron stars.

Although gamma-ray detectors are normally carried into orbit to get them above the earth's atmosphere it has been found that very short (very high energy) gamma rays can be detected from the ground by the light flashes they produce on collisions with air molecules at high altitudes in the earth's atmosphere. The earth's atmosphere is opaque to gamma-rays and gamma-rays don't get through but ones with sufficient energy produce a flash of visible light which can be seen from the ground on a clear night with suitable equipment.

The technique is valuable because it affords a ground-based means of studying the highest energy gamma-rays (above 100 billion electron volts) at wavelengths of the order of one attometer or shorter.

The light produced by the collision is largely beamed forward in the same direction the gamma ray was travelling. The visible light emission is called *Cerenkov radiation* after the Russian physicist, P.A. Cerenkov, who found in 1934 that high energy particles entering air at close to the speed of light produced a visible radiation.

The gamma-ray-air-molecule Cerenkov radiation effect may be described as follows. When the gamma ray (a high energy photon) hits an atomic nucleus its energy may be transformed into an electron (and also a positron) of very high velocity. Due to its high velocity the electric field of the electron is distorted and an optical shock wave (Cerenkov radiation) is produced in the air. The wave is analogous to the slower acoustic sonic-boom wave from a super-sonic projectile or aircraft.



Light from gamma rays.

Toward a Fuller Spectrum Astronomy

Ancient shepherds, astronomers and other watchers of the sky viewed the heavens with unaided eye. This marvelous organ is responsive to a narrow band of wavelengths, or *visible spectrum,* embracing the rainbow of colors from violet, through blue, green, yellow and orange to red or from 400 to 700 nanometers wavelength. This is the normal range of sensitivity of the human eye. Wavelengths less than 400 nanometers are called *ultra-violet* and wavelengths longer than 700 nanometers are called *infra-red.* Bees' eyes are sensitive to ultra-violet wavelengths almost as short as 300 nanometers and some snakes have receptors or pits sensitive to infra-red or heat wavelengths.

X-rays are shorter than ultra-violet and *gamma rays* shorter still. At the other end of the spectrum beyond the infra-red, wavelengths longer than about 1 millimeter are called *radio waves.*

Galileo's invention of the telescope made it possible to see fainter objects and greater detail but it did not extend the wavelength range beyond that of the human eye. However, with the advent of photography and other related techniques, astronomers extended their range of detection down to 300 nanometers in the ultra-violet and up to about 1000 nanometers in the infra-red.

But beyond that they could not go because the atmosphere is opaque to wavelengths shorter than 300 nanometers and mostly opaque to wavelengths longer than about 1000 nanometers. This range of atmospheric transparency is called the **optical window** and celestial observations from the earth's surface are restricted to this part of the electromagnetic spectrum except for a few narrow windows in the 1 to 35 micrometer region and for a radio window.

It is no coincidence that the wavelength range of human vision lies in the middle of the optical window. Probably as a result of an evolutionary development of the eye, it is most sensitive to those wavelengths for which the sun is brightest and the window most transparent.

About 1930 Karl Jansky discovered radio waves from our galaxy, opening a second "window" into space. This led, in the succeeding decades, to the development of radio astronomy with the radiation from celestial objects being detected at the much longer wavelengths from 1 millimeter to some tens of meters. This wide range of wavelengths is called the **radio window** through which electromagnetic waves from space can reach the earth's surface. The window is cut off at the short wavelength end (about 1 millimeter) by the opacity of the atmosphere while the long wavelength end is cut off, not by the atmosphere, but by an ionized layer or blanket of changed particles called the ionosphere which envelopes the earth at a height of several hundred kilometers.*

Radio astronomy has had a revolutionary effect on our knowledge of the universe, but it has been only a precursor of the further revolution in astronomy that has occurred in the years after Sputnik, in which telescopes for many wavelengths have been lofted into space above the earth's atmosphere and ionosphere. The view from these space telescopes is not limited to the optical and radio windows but is open to a much wider band of wavelengths within a "cosmic window." See diagram on page 221.

Orbiting ultra-violet, x-ray and gamma-ray telescopes have extended our knowledge of the universe to the shortest electromagnetic waves while infra-red telescopes and very long wavelength telescopes in space have stretched the cosmic spectrum to radio wavelengths of 1000s of meters.

We now have entered an era of fuller-spectrum astronomy in which observations of celestial objects can be made over a much wider range of the electromagnetic spectrum, the earth's atmosphere no longer being a barrier to mankind's exploration.

However, data on most celestial objects is still fragmentary and many more observations at more wavelengths will be required to provide complete spectra.

As an example, consider the quasar OQ172*, the most distant known object in the universe. What we know about its spectrum is shown in the **All-Wavelength Spectrum** where the heavy line portions indicate the wavelengths for which actual measurements have been made. These are in the radio, optical, and x-ray regions. The lighter line portions are assumed extrapolations through the infra-red and ultra-violet regions where measurements have yet to be made.

Two spectral curves are shown, one based on observations, and, to its left, the spectrum as it would be if OQ172 were not moving with respect to us instead of receding from us at 91 percent of the velocity of light. The most prominent feature is the Lyman-alpha line of hydrogen which is Doppler or redshifted from the ultra-violet into the middle of the visible spectrum.

Will infra-red and ultra-violet measurements confirm the extrapolations assumed in the diagram or will there be some surprises? As our all-wavelength astronomy matures and observations are made at more and more wavelengths we can hope to find out.

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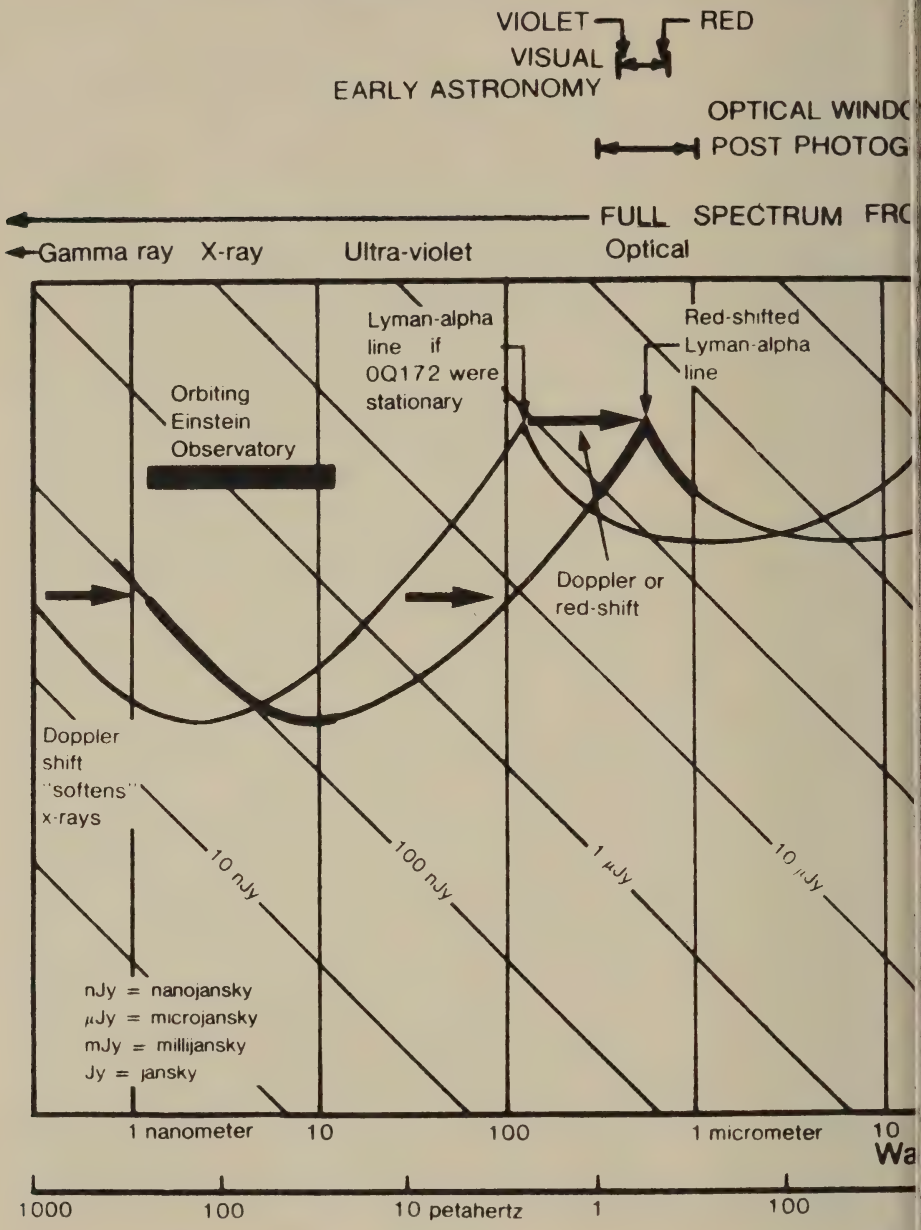
* The long wavelength limit due to the ionosphere is variable and is at longer wavelengths on the night side of the earth because it is shielded from the sun which is responsible for much of the ionization.

* OQ172 is a radio source discovered with the Ohio State University 110-meter telescope. The "O" stands for Ohio while the Q172 indicates the object's position in the sky. (See page 124).

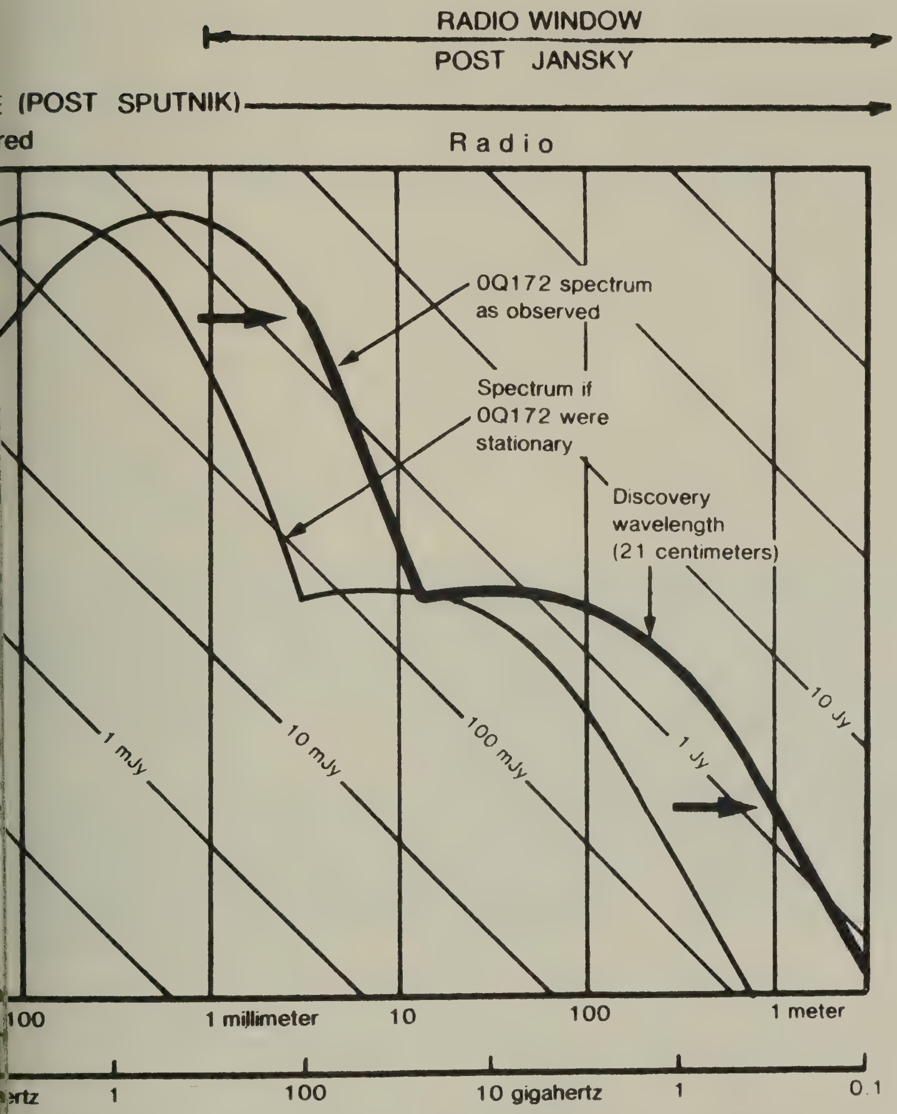
All Wavelength Spectum of 0Q172, th



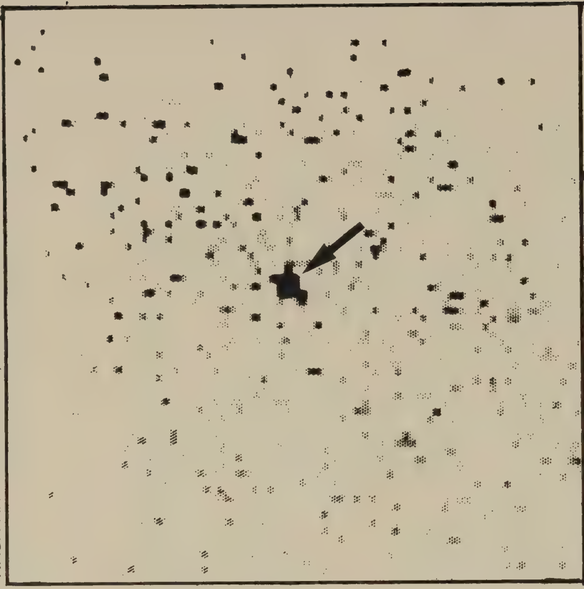
Early astronomers saw the universe through only the narrow visual band of wavelengths. After photography was invented the view was widened to the optical window. Jansky's discovery added the wide radio window and finally following Sputnik, all wavelengths have become available for study from orbiting telescopes.

Strength of radiation from OQ172, the most distant known object in

Distant Known Object in the Universe

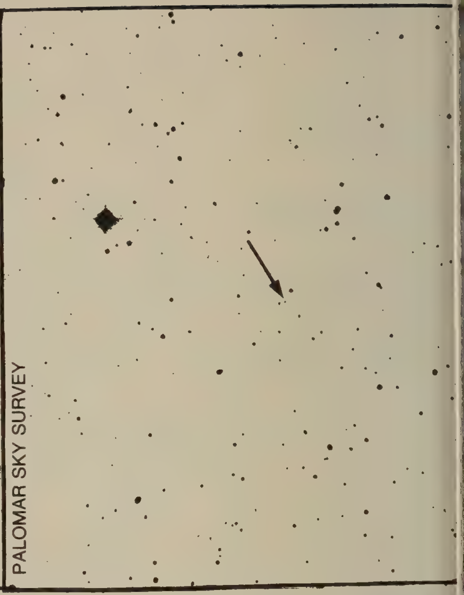


the universe, is shown at x-ray, optical and radio wavelengths by two curves, the right-hand one involving actual measured strengths, while the left one is the way OQ172 would appear if OQ172 were stationary instead of receding from us at 91 percent of the velocity of light. The velocity of light, or other electromagnetic waves from gamma rays to radio waves, is 300 000 kilometers per second.



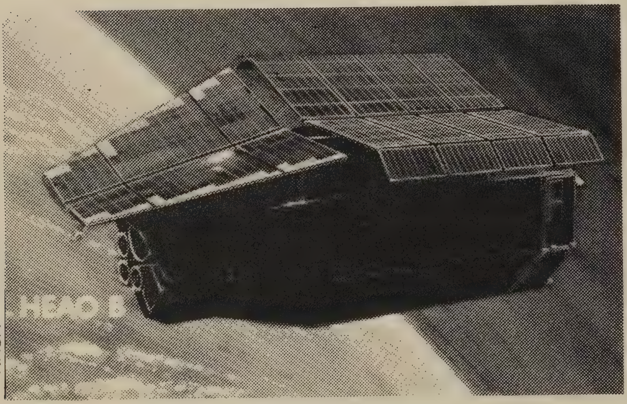
NASA AND WILLIAM KU, COLUMBIA UNIV.

X-ray picture with orbiting Einstein telescope.



PALOMAR SKY SURVEY

Optical picture (negative) with Mt. Palomar Schmidt telescope.



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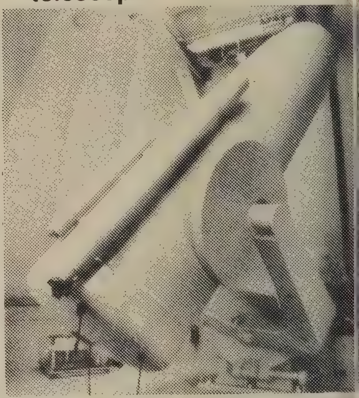
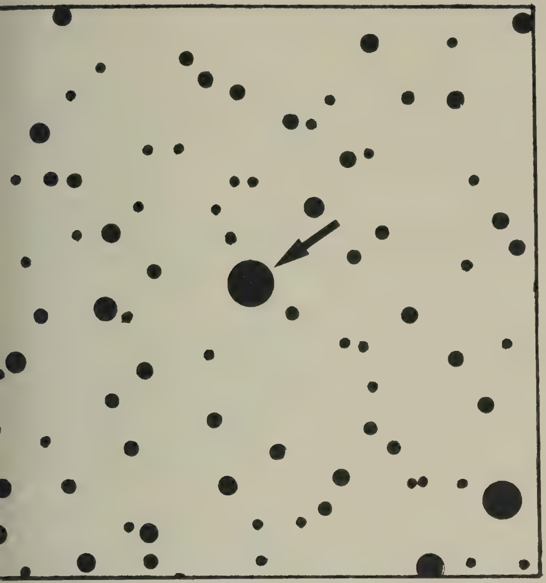


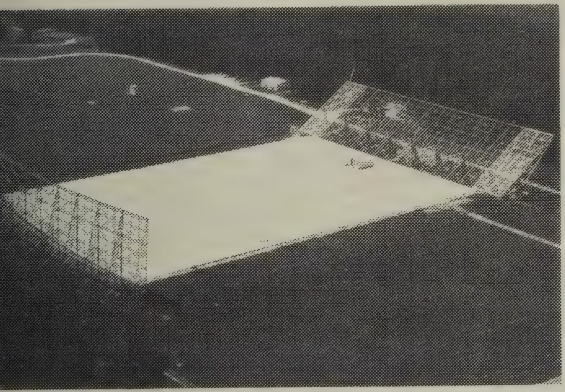
HALE OBSERVATORIES

The way OQ172 appears to x-ray, optical and radio telescopes is shown by these three pictures (see arrows). The telescopes used for these pictures are also shown. Note that whereas OQ172 is prominent in the radio picture, which resulted in its discovery and also in the x-ray picture, it is almost invisible in the optical photograph. Yet it was the optical spectrum that was crucial in establishing the redshift.

The three pictures are, left to right, 1°, ½°, and 8° on a side.



Radio picture with Ohio State University radio telescope.



To summarize:

- All of our early astronomical knowledge was limited to what could be discerned through the narrow optical window.
- In the decades after 1930 a much broader window was opened at radio wavelengths providing a new and different view of the universe.
- In the decades after Sputnik, observations from above the earth's atmosphere and ionosphere became possible and a full-spectrum or all-wavelength window opened on the universe.
- The observations of OQ172 give us an exciting preview of the new era of full-spectrum astronomy we are now entering.

Energy and Number of Photons Received from OQ172 at X-ray, Optical and Radio Wavelengths

	X-ray	Optical	Radio
Energy (femtojoules)	10	10	10
Number of photons	60	100 000	10 000 000 000

Although the Einstein x-ray telescope detected only 60 photons from OQ172, they carried the same energy as 10 billion radio photons.

How Is a Quasar's Redshift Determined and Its Distance Inferred?

In the preceding section we called OQ172 the most distant known object in the universe. How was this determined? The account reads like a detective story:

In 1967 during the Ohio State University 21-centimeter sky survey a strong radio source was discovered which was designated OQ172. The fact that it had not previously been detected in the longer wavelength surveys of other radio observatories suggested that OQ172 had an unusual spectrum. Additional measurements were then made at a Canadian radio observatory.

Next, a French astronomer found that the position of OQ172 in the sky coincided with a faint star-like object. This identification of a "star" (actually a quasar) with OQ172 was then confirmed when a very precise position for OQ172, as measured at an English radio observatory, was found to agree very closely with the "star's" location. With this information in hand, a team of astronomers at the Lick Observatory, California, used a newly developed electronic scanner to obtain an optical spectrum of OQ172 which established its redshift at a recordbreaking 3.53 or 353 percent. Later a wider spectrum was measured with the Palomar 5-meter telescope. Subsequently, a team of 23 radio astronomers at 12 observatories in six countries measured a detailed radio spectrum and recently a group at Columbia University, New York, detected OQ172 at x-ray wavelengths using the orbiting Einstein Observatory (High Energy Astronomical Observatory-2) of the National Aeronautics and Space Administration.

Now let's examine how the high redshift for OQ172 was determined and what this means (See page 181). The Lick Observatory team found peaks of intensity in the optical spectrum which they related to emission from atoms of the elements of hydrogen and carbon in OQ172 but shifted to much longer wavelengths than these same atoms emit in a laboratory here on the earth. The shift is interpreted to mean that OQ172 is rapidly receding from us, the increase in wavelength being due to the Doppler effect.

More explicitly the Lick Observatory team found a very prominent peak at 554 nanometers and a weaker one at 702 nanometers. These wavelengths have the same ratio that a pair of prominent hydrogen and carbon lines have in the laboratory where their wavelengths are 122 and 155 nanometers, respectively.* Thus, the Lick team could conclude that the emission peaks were due to atoms of hydrogen (Lyman-alpha line) and triply-ionized carbon (three electrons missing) but with both lines Doppler shifted to longer wavelengths because OQ172 was receding from us at the unprecedented velocity of 91 percent of the speed of light and was at a distance of nearly 14 billion light-years in a universe of 15 billion light-years radius (See **Spectral-Line Redshift Diagram for Quasars.**)

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* The **redshift** is equal to the difference of the shifted and unshifted wavelengths divided by the unshifted wavelength. Thus, we have $(702 - 155) \div 155 = 3.53$ or 353 percent for the carbon line and $(553 - 122) \div 122 = 3.53$ or 353 percent for the hydrogen line.

The 353 percent redshift for OQ172 is an experimental result which stands on its own. If the spectral peaks are actually due to atoms of hydrogen and carbon, as seems well established, the redshift value is not subject to interpretations or assumptions. However, the velocity and distance values are *inferred* results which depend on the assumption that OQ172 is receding from us in a universe which is expanding uniformly (with a certain Hubble constant) presumably following an initial Big Bang. The redshift might be interpreted in other ways, but the interpretation we have made is the one accepted by most astronomers.

Although the above discussion indicates the general procedure, it is greatly oversimplified and much more enters into the various steps. For example, the hydrogen and carbon lines of OQ172 are also found in other quasars of lesser redshift, which lends confidence that the analysis is correct.

The principal atomic emission lines used for determining the redshifts of quasars are shown in the **Spectral-Line Redshift Diagram**. All of the quasars listed were discovered with radio telescopes, then identified with an optical object (quasar) and finally an optical spectrum obtained with emission lines which could be identified unambiguously with atomic elements. The radio sources were like arrows directing the attention to what might otherwise be regarded as very faint, ordinary stars.

As the redshift increases, the observed wavelength of the emission lines becomes longer so that lines normally in the visible (at zero redshift in an earth laboratory) move into the infra-red, while lines in the ultra-violet (notably the Lyman-alpha line) shift into the visible. The solid dots on the lines indicate that these particular lines were used in the redshift determination of a particular quasar. The half-circles (at zero redshift) indicate the wavelength of the lines for a stationary source, as in a laboratory on the earth. For smaller redshifts (under 50 percent) the lines of magnesium, neon and hydrogen (Balmer beta and gamma lines) were the keys to the redshift,* while at higher redshifts of 200 percent or more, a carbon line and the Lyman-alpha line of hydrogen were the keys. Note how the two dots on

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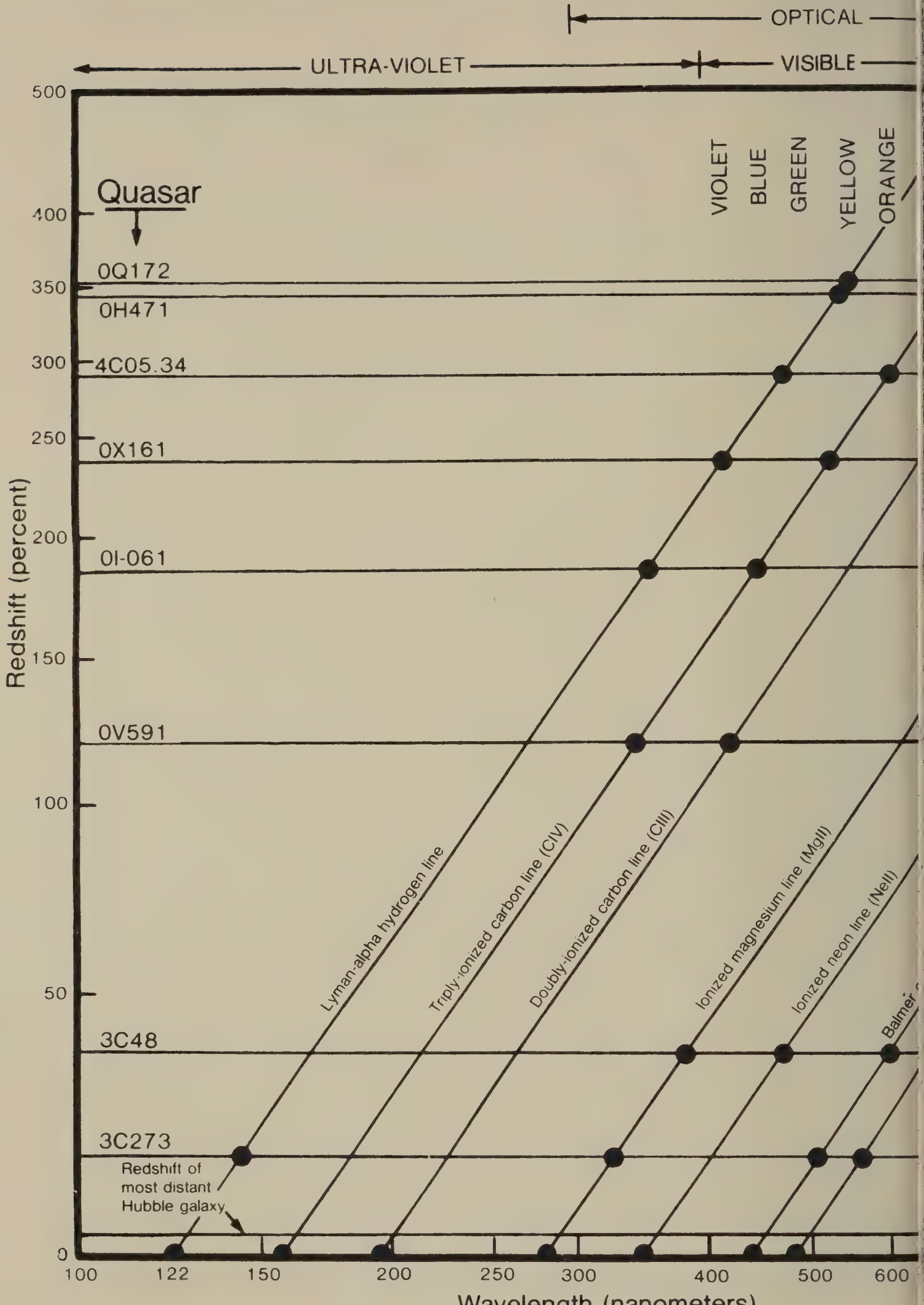
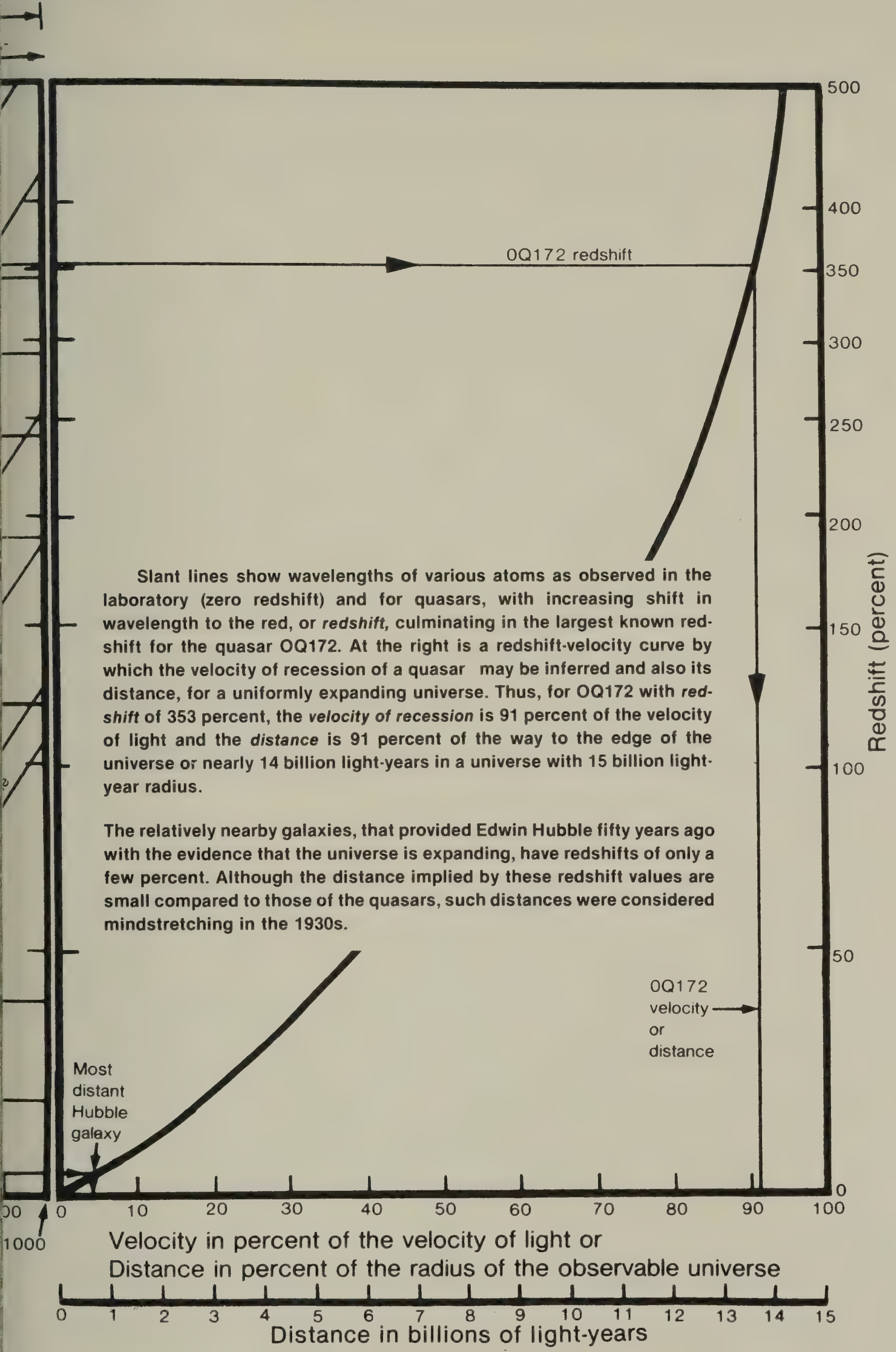
* See page 106.

Spectral


OPTICAL
ULTRA-VIOLET
VISIBLE
VIOLET
BLUE
GREEN
YELLOW
ORANGE
Quasar
0Q172
0H471
4C05.34
0X161
0I-061
0V591
3C48
3C273
Redshift of most distant Hubble galaxy
Lyman-alpha hydrogen line
Triply-ionized carbon line (CIV)
Doubly-ionized carbon line (CIII)
Ionized magnesium line (MgII)
Ionized neon line (NeII)
Balmer
Redshift (percent)
500
400
350
300
250
200
150
100
50
0
100
122
150
200
250
300
400
500
600
Wavelength (nanometers)

dshift Diagram for Quasars



Slant lines show wavelengths of various atoms as observed in the laboratory (zero redshift) and for quasars, with increasing shift in wavelength to the red, or *redshift,* culminating in the largest known redshift for the quasar OQ172. At the right is a redshift-velocity curve by which the velocity of recession of a quasar may be inferred and also its distance, for a uniformly expanding universe. Thus, for OQ172 with *redshift* of 353 percent, the *velocity of recession* is 91 percent of the velocity of light and the *distance* is 91 percent of the way to the edge of the universe or nearly 14 billion light-years in a universe with 15 billion light-year radius.

The relatively nearby galaxies, that provided Edwin Hubble fifty years ago with the evidence that the universe is expanding, have redshifts of only a few percent. Although the distance implied by these redshift values are small compared to those of the quasars, such distances were considered mindstretching in the 1930s.

these lines for the quasar OI-061 at about 200 percent redshift move to the right or to longer wavelengths as the redshift increases, culminating in the values for the highest redshift quasars OQ172 and OH471. It is apparent that for a hypothetical quasar with a redshift of 500 percent these lines will be shifted entirely out of the visible spectrum.

When Professor Theodore Lyman first succeeded in observing the 122 nanometer line of hydrogen (now known as the Lyman-alpha line) in a Harvard physics laboratory in 1905, he could not have forseen that 7 decades later this line would be found in the spectrum of faint quasars but shifted from the ultra-violet into the visible and play a key role in determining their large redshift and enormous distance.

What can be said about the nature of the quasars, such as OQ172? Although a quasar is quasi-stellar in appearance, or looks like a star, it is in reality a much larger object. A quasar is believed to be a galaxy or aggregation of many stars with a very dense, powerful nucleus which, because of its great distance from us, appears as a single star-like point of light. For OQ172, the Lick Observatory team measured not only 353 percent redshift for hydrogen and carbon emission lines but also hundreds of absorption lines involving additional elements in intervening regions of gas, suggesting that the emitting nucleus of OQ172 is surrounded by expanding clouds of gas thrown off, perhaps, by a succession of great explosions. From all these lines there is evidence that atoms of hydrogen, carbon, silicon, sulphur and nitrogen are present in OQ172.

To summarize:

- When radiation from the atoms of a quasar can be correlated with the emission of the same kind of atoms in a laboratory on the earth, the quasar's redshift can be calculated.
- The difference in the wavelengths of the quasar atoms and the earthbound atoms is a measure of the redshift, the greater the difference, the greater the redshift.
- The quasar OQ172 has the largest known redshift, equal to 353 percent.
- A redshift of 353 percent may be interpreted to mean that OQ172 is rushing away from us at a velocity of 275 000 kilometers per second and that it is at a distance of nearly 14 billion light-years.

HAT DO THE DIFFERENT WAVELENGTHS OF THE FULL-SPECTRUM ASTRONOMY TELL US?

- **Radio Wavelengths** reveal electron clouds around stars and galaxies as well as hydrogen and molecular clouds. Radio telescopes have located many exploded stars (supernova remnants) and exploded galaxies.

- **Infrared Wavelengths** reveal relatively cool, new stars, formed by contraction of gas and dust clouds, and also older red stars. The primordial remnant radiation from the Big Bang is strongest at long infra-red or very short radio wavelengths.

- **Optical Wavelengths** provide a wealth of information about stars and galaxies including the atomic elements present, temperature, rotation, magnetic fields and velocity of recession or approach.

- **Ultra-Violet Wavelengths** reveal hot stars, blue stars, stars in the process of contraction and also older (contracted or collapsed) white dwarf stars.

- **X-rays** come from stars, particularly hot, blue ones, from quasars, from neutron stars (pulsars) where infalling gas is compressed by the strong gravity and heated to a high temperature, and from exploded stars (supernovas).

- **Gamma rays** come from extremely hot regions which may also emit x-rays. Gamma ray pulses are thought by some to come from the explosion of mini-black holes. A long wavelength gamma ray is like a short wavelength x-ray.

Great Dates in Instrumental Astronomy

1610	**Galileo**	**First optical telescope**
1930	**Jansky**	**First radio telescope**
1970	**UHURU***	**First orbiting x-ray telescope**

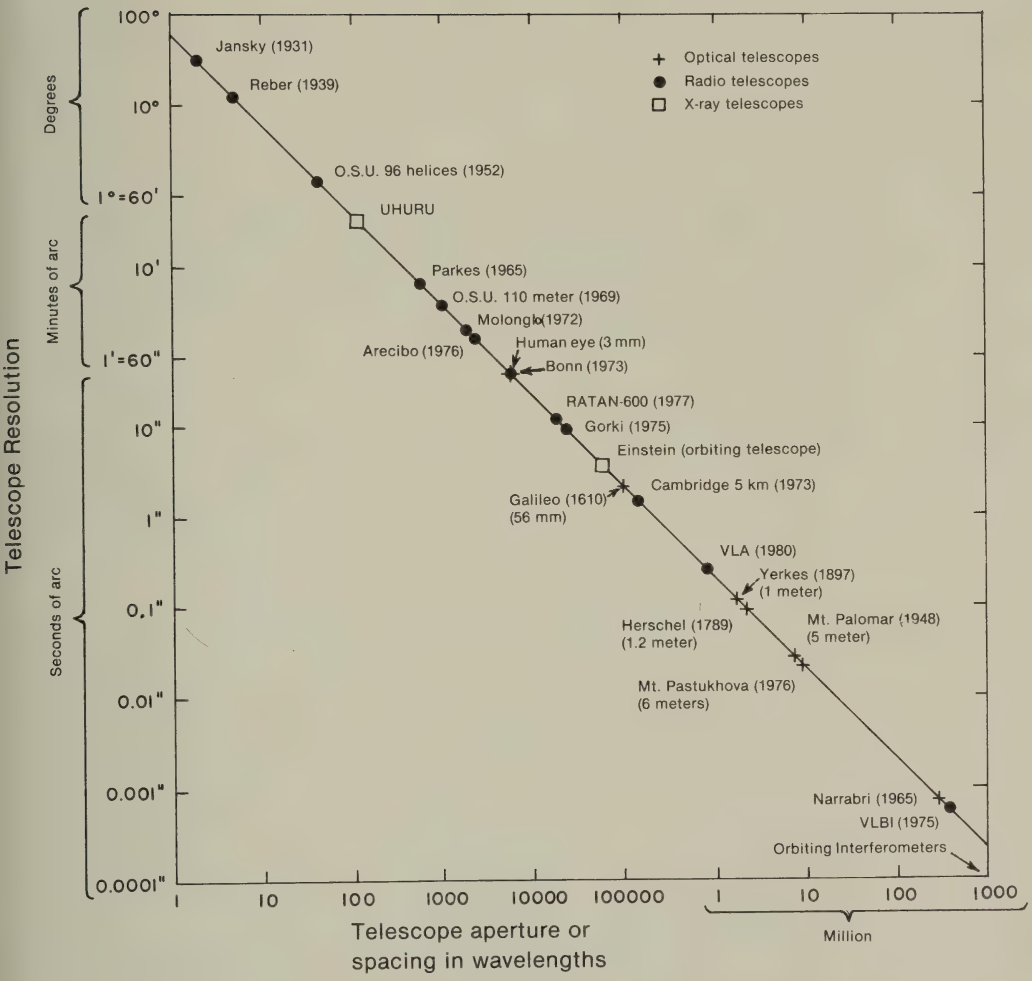
* Although rocket borne x-ray devices had obtained brief glimpses of the x-ray sky from above the earth's atmosphere as early as 1960, the first full-time survey of the x-ray sky began December 12, 1970, with the launching of UHURU (pronounced oo-hoo-ru) from a platform off the coast of Kenya. The launch date coincided with the 7th anniversary of Kenya's freedom, UHURU being the Swahili word for "freedom". UHURU was the first of a series of High Energy Astronomy Observatories (HEAO) built by the National Aeronautics and Space Administration for studying x-rays from space.

Old Stars: Red Giants, White Dwarfs, Pulsars and Black Holes

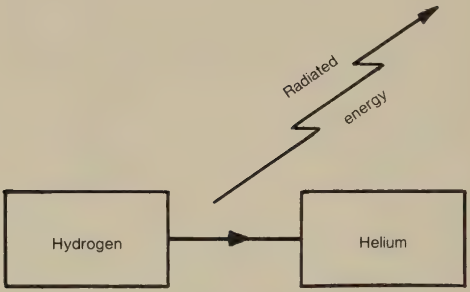
The nuclear fusion powering a star converts lighter elements into heavier ones (hydrogen to helium to carbon, etc.). When such stars run out of fuel and collapse with an accompanying violent explosion, space is enriched with heavier elements. From this material new stars may form and the process be repeated. For example, the atoms of which you and I are made were formed in the nuclear transformations of a star billions of years ago, the star then ejecting the atoms into space. Eventually, the sun, earth and other planets condensed out of this material. The statement is sometimes made that we are, in a very real sense, "star folk."

The fusion process (hydrogen to helium) powering the star continues until the hydrogen in the core becomes depleted, after which helium burning or fusion can occur to produce carbon and heavier elements. The star begins to expand, leaving the main sequence and radiating more power until it reaches the stage of a red giant. The time interval from main sequence to red giant may be something like a billion years. After a shorter period as a red giant the star may begin to contract while increasing in temperature until after as much as 100 million years, with nuclear fuels being depleted, gravitational collapse occurs.

Resolution of Telescopes

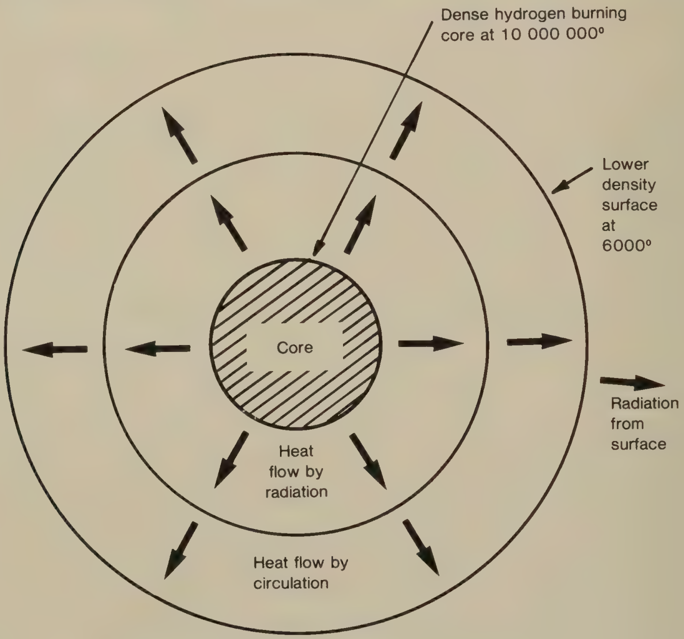


Resolution of radio and optical and x-ray telescopes as a function of the telescope aperture or spacing. From Jansky and Reber and their radio telescopes of the 1930s, the resolution of radio telescopes has increased (resolution angle smaller) over the years until by 1975 the VLBI (Very Long Baseline Interferometer), using the earth's diameter for the spacing between antennas, has achieved a resolution equal to or better than that of the largest optical devices. Data for the graph are tabulated on page 264.

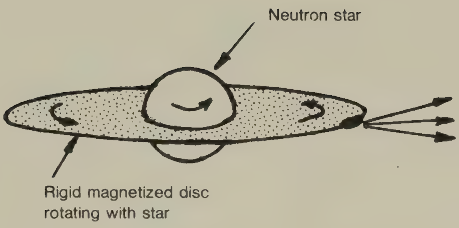


Hydrogen converts to helium with some loss of mass. The lost mass changes into energy according to Einstein's equation $E = mc^2$ (energy equals mass times the velocity of light squared). Thus, if we take 130 grams of hydrogen, 129 grams will be converted into helium and 1 gram into 25 million kilowatt-hours of energy.

As the inner part or core of the star collapses, it may heat up to a billion kelvins and radiate sufficiently at x-ray and gamma-ray wavelengths to blow a layer or shell surrounding the core outward which carries off the outer portion of the star in a vast supernova explosion with the attendant emission of electromagnetic radiation of all wavelengths. The supernova ex-


Dense hydrogen burning core at 10 000 000°
Lower density surface at 6000°
Core
Radiation from surface
Heat flow by radiation
Heat flow by circulation

Cross-section of a star like the sun.

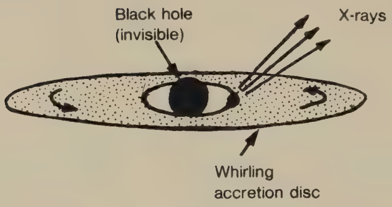


A pulsar is a super-dense neutron star with an enormous magnetic (as well as gravitational) field that, in the model shown, has a disc of magnetized plasma (of charged particles) rotating with it as though frozen on. The edge of the disc may be travelling at the velocity of light with x-rays coming off from the rim, like sparks from a grinding wheel, as the rim interacts with the surrounding medium. In this example, the magnetic axis of the pulsar lies in the plane of the disc and is perpendicular to the rotation axis. The neutron star, or core of the pulsar, may be only about 10 kilometers in diameter while the disc may be several thousand. Drawing not to scale.

plosion may blast off half or more of the star's mass forming a huge expanding cloud. The core in the meantime collapses further into a neutron star (pulsar) or if the star is sufficiently massive it may collapse so energetically that it collapses into a black hole with attendant radiation of a gravity wave pulse. Under somewhat different circumstances a star's collapse may cause it to end up as a white dwarf.

The power-temperature or Hertzsprung-Russell chart (page 53) traces the evolutionary track of a typical star from its birth as an infra-red object through its contraction to a main sequence star followed by expansion to a red giant, further contraction and catastrophic collapse, and ending as a white dwarf, neutron star or black hole. The track from birth to main sequence could describe the evolutionary history of the sun. The post main-sequence track might also indicate what may happen to the sun some billions of years hence. Although the sun could end up as a white dwarf, it is not massive enough to end up as a black hole.

A black hole is a fantastic object. From inside a critical distance or "event horizon" nothing can escape, not even light or other electromagnetic waves. However, the hole's presence is manifest to its surroundings by its enormous gravitational field. Thus, although itself invisible, a black hole may be surrounded by an accretion disc formed of compressed gas sucked from a

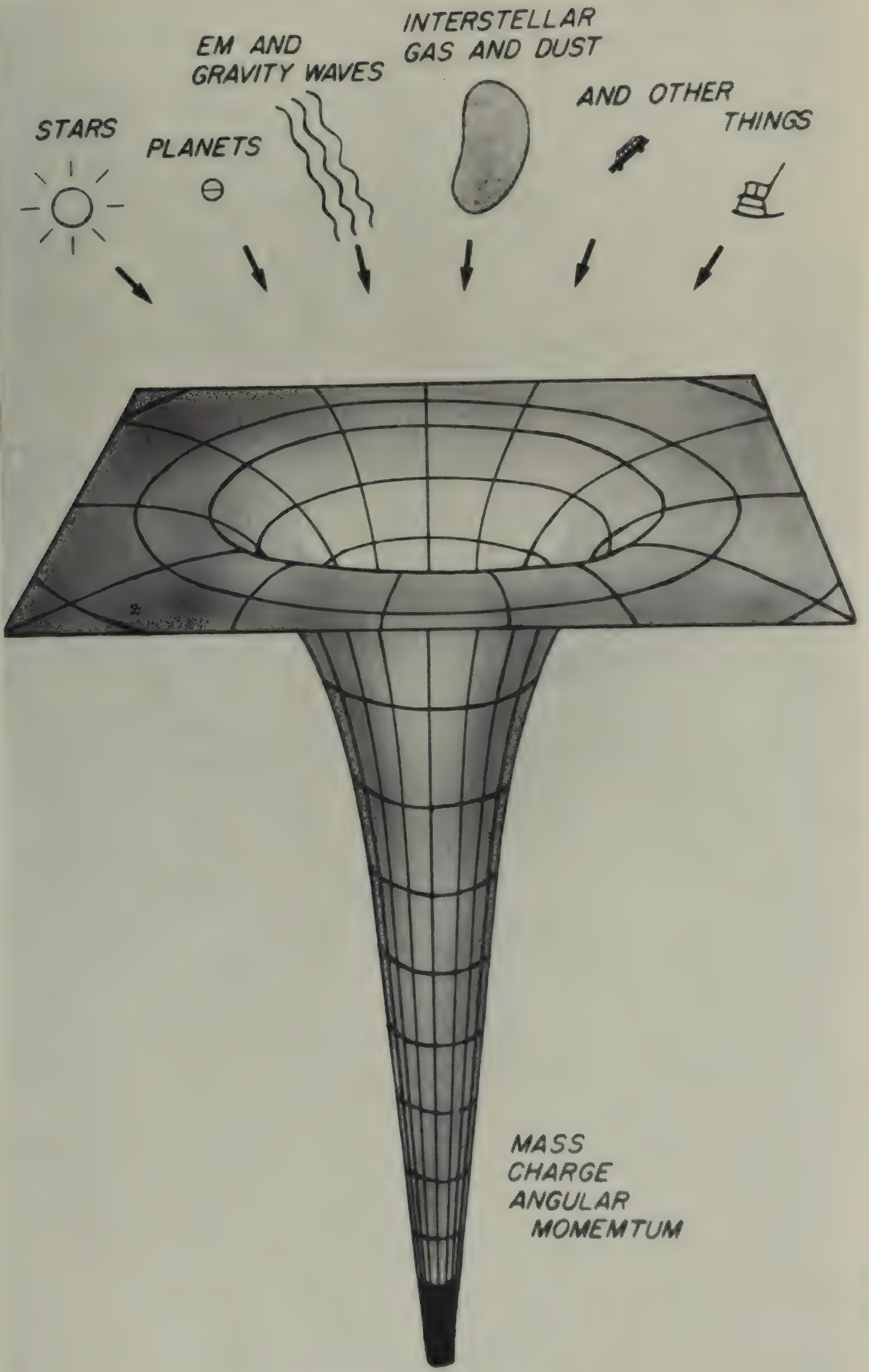


Close-up of accretion disc with invisible black hole (inside dotted circle) in the eye of the disc. The disc is formed of gas pulled from a companion star, the gas swirling around as it is drawn relentlessly closer to the hole. X-rays are emitted from the inner edge of the disc. Light emitted from regions outside the hole will be deviated or bent, as though by a lens, by the hole's gravitational pull tending to distort or blur any picture.

companion star and whirling around the hole like water around the eye of a whirlpool. At the inner edge of the whirling disc just before the gas falls into the hole, its temperature may be sufficiently great that intense x-rays are emitted.

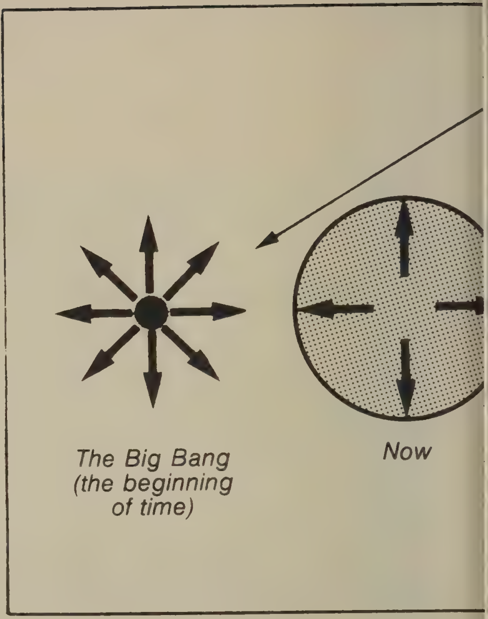
All details of infalling material are wiped out in a black hole, only the net mass, angular momentum and electric charge being significant. A black hole is the ultimate trash compactor; what falls in can never get out except in one special case. (See footnote on page 263). Although the black hole itself may be only a kilometer or so in circumference, the accretion disc may be thousands of kilometers in diameter.

Diagrammatic representation of a black hole suggesting how space is curved or warped by its enormous gravitational pull. All details of infalling material are wiped out in the black hole, only the net mass, charge and angular momentum remaining. A black hole is the ultimate trash compactor.


STARS
PLANETS
EM AND GRAVITY WAVES
INTERSTELLAR GAS AND DUST
AND OTHER THINGS
MASS
CHARGE
ANGULAR MOMEMTUM

"The universe starts with a Big Bang, expands to a maximum dimension, then recontracts and collapses (to the Big Crunch); no more awe-inspiring prediction was ever made." Quotation from Charles W. Misner, Kip S. Thorne and John A. Wheeler in "Gravitation", W.H. Freeman, San Francisco, 1973, page 1196.

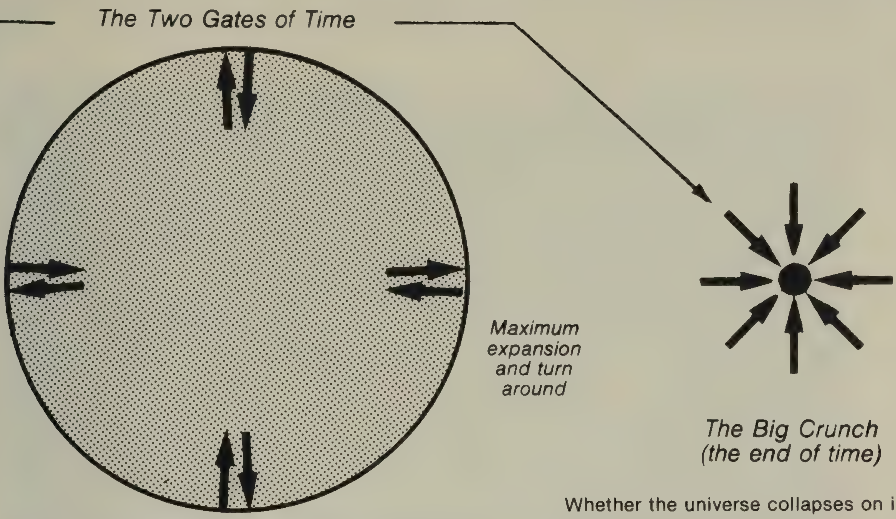
We are now nearer the Big Bang than the Big Crunch since the universe, as we observe it, is still expanding.



DIMENIONS OF A TYPICAL STAR AND OF THREE COLLAPSED STARS

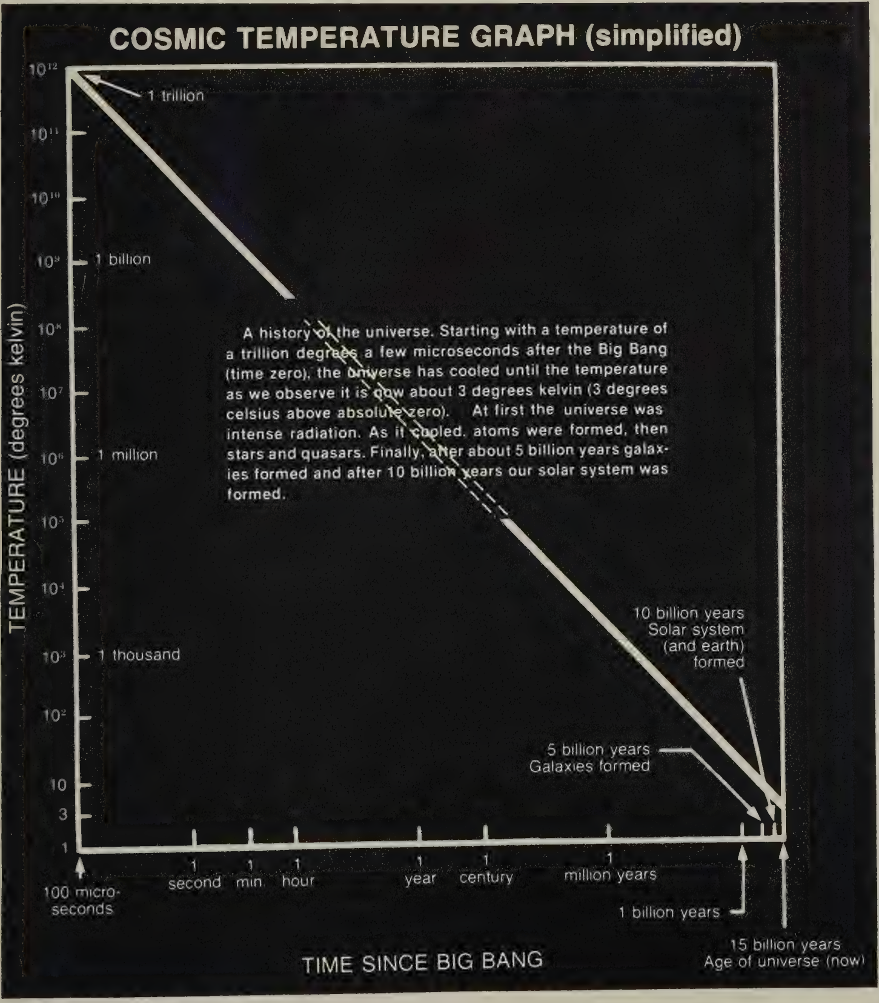
Object	Diameter (approx.)
Star (such as sun)	1 000 000 kilometers = 10^9 meters
White dwarf	10 000 kilometers = 10^7 meters
Neutron star or pulsar	10 kilometers = 10^4 meters
Black hole	less than 1 kilometer = 10^3 meters

The density of a neutron star is such that a thimble full weighs as much as 50 000 Empire State Buildings. The density of a black hole is much greater.


The Two Gates of Time
Maximum expansion and turn around
The Big Crunch (the end of time)

The Complete Story of the Universe

Whether the universe collapses on itself as depicted here or continues to expand indefinitely is an actively pursued question.



A history of the universe. Starting with a temperature of a trillion degrees a few microseconds after the Big Bang (time zero), the universe has cooled until the temperature as we observe it is now about 3 degrees kelvin (3 degrees celsius above absolute zero). At first the universe was intense radiation. As it cooled, atoms were formed, then stars and quasars. Finally, after about 5 billion years galaxies formed and after 10 billion years our solar system was formed.

AFTER R.H. DICKE, ASTROPHYSICAL JOURNAL

The Mysterious SS433

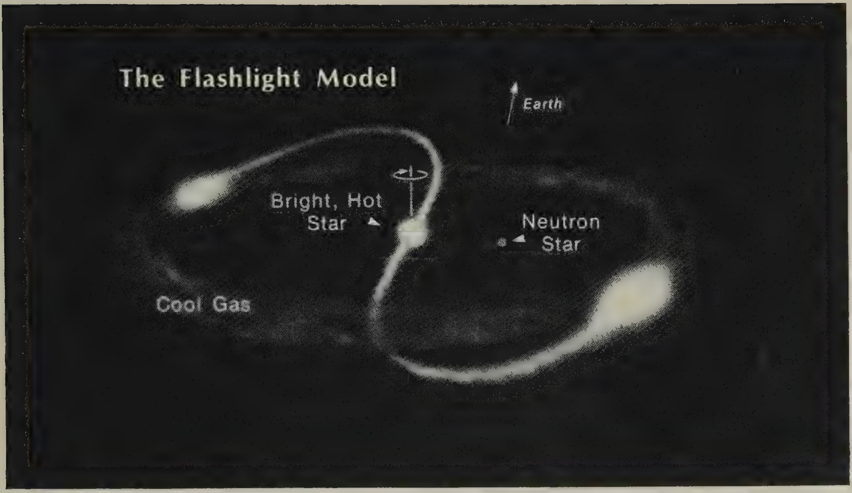
In 1958 during a survey of the galactic plane with the Dwingeloo, Holland, radio telescope, Gart Westerhout discovered a radio source now known as W50 (for Westerhout 50). The source is apparently a distant supernova remnant in our galaxy. Subsequently, at the center of W50, a radio source of star-like dimensions was found, which also emitted x-rays, and this object coincided in position in the sky with an unusual star listed as number 433 in a catalog published in 1977 by C.B. Stephenson and Nicholas Sanduleak of Case Western Reserve University, Cleveland, Ohio. The object, now known as Stephenson-Sanduleak 433 or SS433 for short, is believed to be at a distance of about 12 000 light-years.

In 1979 Bruce Margon and associates of the University of California (Los Angeles) and James Liebert of the University of Arizona and his associates announced that they had observed optical emission lines from SS433 to shift in wavelength with a period of about 165 days. But most remarkably, if the shifts were a Doppler effect, they indicated motions of as much as 17 percent of the velocity of light away (a redshift) and simultaneously as much as 10 percent toward us (a blue shift).

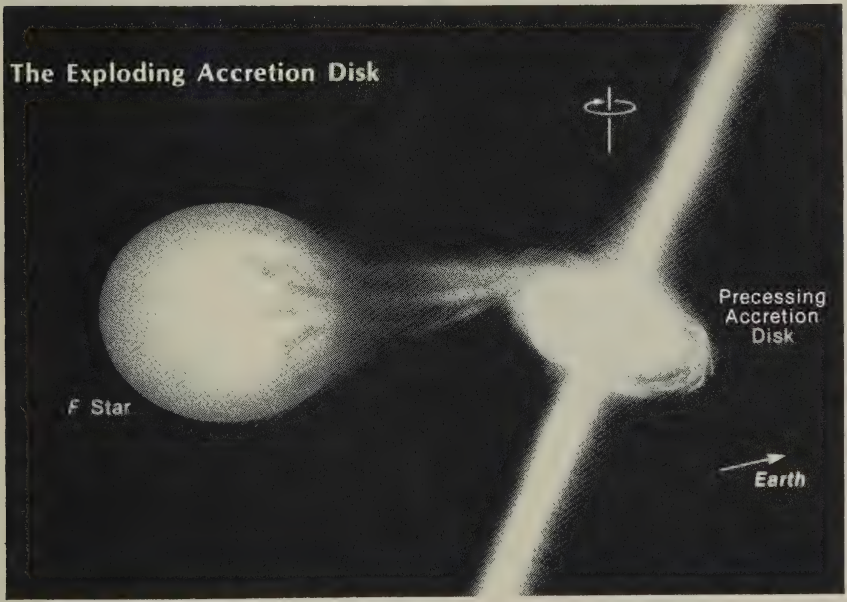
The object is unique and although its true nature is uncertain, a couple of theories have been advanced to explain its unusual characteristics. One theory, proposed by George Collins II, Gerald Newsom and R.N. Boyd of the Ohio State University, involves a spinning bright blue star swinging around another less massive star. A strong particle wind blows outward in opposite directions from the magnetic poles of the blue star, like water from a slowly rotating lawn sprinkler making about 2 revolutions per year, until at a large distance, many times greater than the diameter of our solar system, the particle wind impinges on a ring of more stationary particles causing it to glow in two places, one of which is approaching and the other receding.

Another theory, advanced by Bruce Margon and George Abell of the University of California (Los Angeles) involves a normal star and a neutron-star companion in which particles drawn off the normal star onto the accretion disc of the neutron star blast outward in opposite directions producing two rotating glowing beams of particles.

It is not uncommon to have more than one theory for astronomical phenomena with more experimental evidence being needed to decide which, if either, is correct.



Bizarre object SS433 may be a powerful blue star blowing matter out its magnetic poles. The matter consisting of charged particles then streams into a spiral.



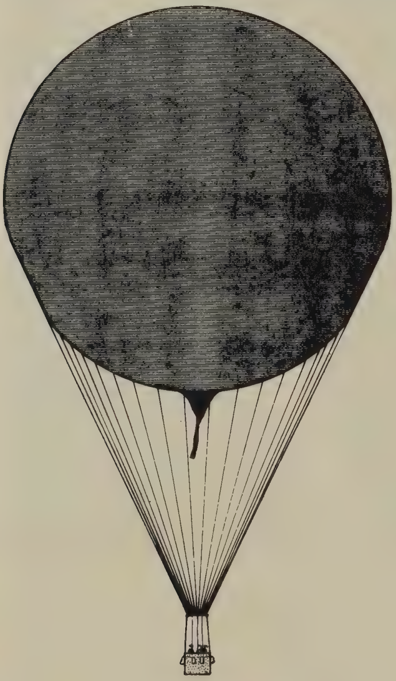
Another explanation for SS433 is that gas flowing from a normal star onto the accretion disc of a companion neutron star blasts outward from the disc. (Diagrams on this page reproduced by permission from "Sky and Telescope," © 1980 Sky Publishing Corp.)

Victor Hess and Cosmic Rays

The linden and willow-lined meadow near Aussig in northern Bohemia had been active since the earliest light of morning. Nearby the river Elbe flowed northward to the Erz mountains whose azure peaks shimmered in the distance against a cloudless sky. Now a few hours after dawn a huge orange and black balloon towered majestically above the meadow's grassy expanse, the low slanting rays of the sun glinting off its rounded dome. Named the *Boehmen* (German for Bohemia) it stood twelve stories high. Nudged by an almost imperceptible breeze, the big bag tugged impatiently on its ropes. Members of the Austrian Aeroclub moved with a well-practiced efficiency making final preparations for its ascension but one could detect a feeling of excitement in the air for this was no ordinary flight.

It was Wednesday the seventh of August, 1912, and today the *Boehmen,* with its lifting power of two tons, was to carry Herr Doktor Victor Hess and a load of his apparatus on a high altitude flight. Hess, 29, taught physics at an academy of veterinary medicine in Vienna. He was already aboard checking his equipment. The flight meterologist, Ernst Wolf, was also in the rope-festooned basket adjusting the barometer.

Inflation was complete and the Aeroclub members disconnected hoses from hydrogen tanks on wagons nearby. Captain Wolfgang Hoffory, the pilot, walked around the outside of the basket inspecting the sand-filled



The ascent of the Boehmen.

Victor Hess surrounded by Austrian peasants after landing from one of his ascensions a few weeks before his record breaking ascent in the Boehmen. (Courtesy of Alphonz Weber)

ballast bags hanging from its perimeter. Shouting final orders to the ground crew he swung effortlessly aboard. He was a veteran of many ascensions and had, in fact, piloted Dr. Hess on a number of flights during the previous months. But none went as high as he hoped to rise today.

At twelve minutes past six Captain Hoffory gave the command to cast off and slowly the great rotund *Boehmen* rose gracefully and silently into the sky seeking the source of a strange radiation.

For many years scientists had puzzled over the fact that an electroscope gradually lost its charge even though it was carefully insulated. Electroscopes had come into wide use after the discovery of radioactivity by Antoine Becquerel of France in 1896. A typical electroscope consists of two leaves of gold foil suspended from an insulated electrode or metal rod in a metal container with glass window. When given an electric charge, as from a rubber comb rubbed with a flannel cloth, the leaves spring apart due to the repulsion of their like charges. Radiation from radioactive material brought near the electroscope penetrates the container producing ions or charged particles in the air inside which discharges the leaves and causes them to drop. What the scientists had noted was that, even in the absence of any known radioactive material, the leaves would gradually drop, suggesting some unknown radiation. It was suspected, and later confirmed, that the radiation came at least in part from the weak radioactivity of substances present near the surface of the earth.

By measuring the rate at which the leaves collapse one can determine the strength of the ionizing radiation. If the pressure of the air in the container enclosing the leaves is increased, the electroscope becomes more sensitive and these so-called *ionization chambers* were carried to the top of the Eiffel tower and aloft in balloons to determine if the radiation decreased with height above the ground but the results were inconclusive.

Victor Hess had wondered if the unknown radiation might come from outside the earth, perhaps from the sun. With support from the Royal Vienna Academy of Science, he had embarked on a series of balloon ascensions at night, during the day and even one during an eclipse of the sun. From these he concluded that the sun was not the source of the mysterious ionizing radiation.

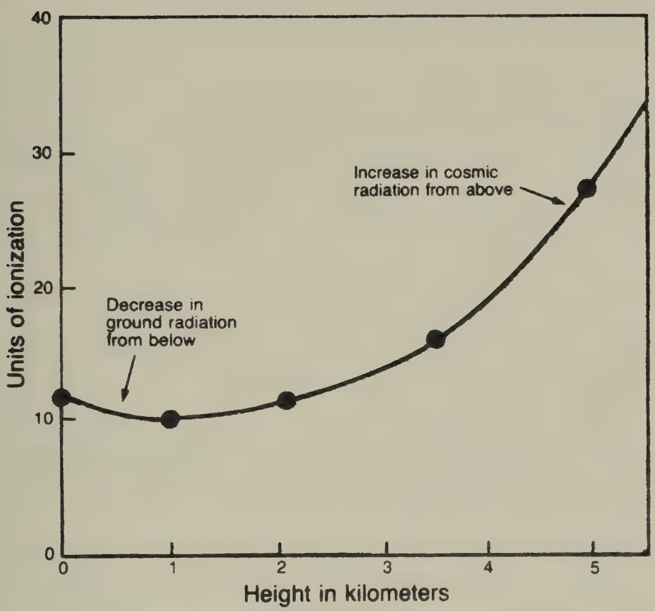
The flight today was the seventh in a series he had begun in April, 1912, and his aim today was to go much higher than he had before. The previous ascensions indicated that there was a small decrease in ionization going from the ground to heights of a few hundred meters due apparently to a reduced effect of the earth's radioactivity. However, with further increase in height up to 2000 meters the readings did not seem to change.

The *Boehmen* was now rising rapidly and catching a 30 kilometer per hour wind from the south, began to follow the Elbe northward over the Bohemian countryside. Soon clouds appeared ahead. They were scattered, puffy, white cumulus clouds, all at the same altitude. The *Boehmen* climbed through them and now, viewed from above, they dotted the landscape like balls of cotton all the way to the horizon. Near Peterswalde the balloonists crossed into Saxony and smoke floating up lazily from the factories of Dresden appeared off to the west.

An hour after lift-off they were at 1600 meters and during the next two hours they rose to 3600 meters. The sun climbing in the east warmed the balloon increasing its lift so Captain Hoffory could conserve on the amount of sand ballast he had to release.

At 10:45 they attained 5350 meters, their maximum altitude, and Captain Hoffory pulled a valve to release some gas and start their gradual descent. Above them at about 6000 meters, there was now a thin filmy layer of strato-cirrus clouds through which the sun shone brightly.

Victor Hess had been busy from before lift off with his apparatus consisting of three ionization chambers and associated equipment. Each chamber was made of an airtight, thick-walled metal cylinder the size of a



Readings on ionization chamber Victor Hess carried aloft in the Boehmen. Above four kilometers the ionization rose rapidly indicating "that rays of very great penetrating power are entering our atmosphere from above". These cosmic rays contain the only modern samples of matter from outside our solar system which can be investigated directly.

two liter can with a small glass window for observing the electroscope leaves with the aid of a microscope. Hess took readings on all three instruments in rotation as the cold thin air of the high altitudes penetrated his clothing. He carefully recorded these values along with the barometric pressure readings which indicated the altitude, as called out by Ernst Wolf.

On chamber number 2, which was rather typical of the three instruments, the ionization at the ground was about 12 units. At an altitude of 1000 meters it dropped to 10 but at 2000 meters the reading was up again to 12. At 3500 meters the ionization level had climbed to 15 and most startingly at 5000 meters it rose to 27 units or more than twice its value on the ground!

The descent was gradual, taking another two hours. On the way down Victor Hess continued to take readings which confirmed the ones he obtained on the ascent. At fifteen minutes past noon Captain Hoffory brought the *Boehmen* down in a pasture near a small village about 50 kilometers east of Berlin. They had been aloft six hours, traveled 200 kilometers and reached a maximum altitude of 5350 meters.

Victor Hess had been so preoccupied with his instruments and recording of the data that the full import of his results did not strike home until after the flight when he had time to analyze the data carefully. But then there was no doubt. The increase with altitude demonstrated that it must be caused from above. The atmosphere was like an absorbing blanket. The higher one rose through it the stronger the radiation from above became. In his report published later that year in the *Physikalisches Zeitschrift* he stated,

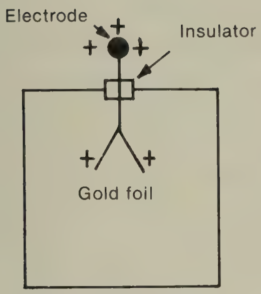
“The results of the observations indicate that rays of very great penetrating power are entering our atmosphere from above.”

During the next two years confirmation of Hess' results came from further balloon flights by Werner Kohlhoerster which culminated in an ascension to 9300 meters from Bitterfield, near Leipsig, Germany on June 28, 1914. Rising above the height Hess had reached, Kohlhoerster found that the ionization continued to increase at an increasing rate. But not every one was convinced by Hess' and Kohlhoerster's observations and a violent controversy ensued in scientific circles which raged for a dozen years.

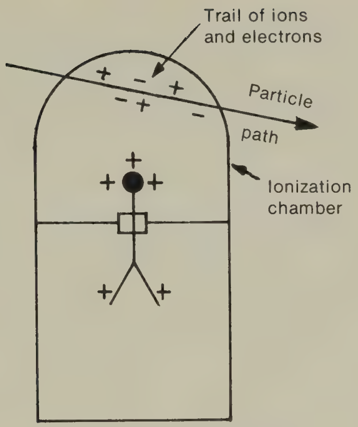
On the same day as Kohlhoerster's 9300 meter flight Archduke Francis Ferdinand, heir to the throne of Austria-Hungary, was assassinated and soon armies were on the march as Europe exploded and plunged into World War I. Strange radiations penetrating the earth's atmosphere from above now seemed of little consequence and further balloon measurements would have to wait.

Eventually Hess's results gained acceptance and the radiations he had discovered coming from beyond the earth were named *cosmic rays.* Perhaps, it was thought, they might be electromagnetic waves like x-rays, only of a more penetrating kind. Subsequently, however, they were shown to be material particles and not waves: protons (hydrogen atom nuclei), electrons and nuclei of heavier atoms to at least uranium, often with enormous energy and penetrating power, which bombard the earth relentlessly. In 1936, Victor Hess received the Nobel prize for his discovery of cosmic rays.

The origin of cosmic rays is uncertain but it is presumed that many are generated during violent events, such as stellar explosions within our galaxy. It is entirely possible that a proton striking the earth today was shot out from the Crab nebula, the exploded star of 1054 A.D. In its journey from the nebula, it has traveled at nearly the speed of light over a path thousands of light-years in length. Magnetic fields encountered along its way have deviated its path from a straight line, like cross-winds buffet a ship off course, so its direction on reaching the earth is not that of the Crab nebula. But this tiny particle is a messenger from a distant part of our galaxy with perhaps a fascinating tale to tell if it could.



Electroscope.



Electroscope with ionization chamber.

The term cosmic ray can refer not only to those particles which bombard the earth from outer space, but also other particles produced when collisions occur with molecules of the atmosphere.

The particles arriving from outer space are called *primary cosmic rays.* These consist largely of protons (hydrogen atom nuclei) and the nuclei of heavier atoms such as helium, carbon, nitrogen, oxygen, silicon, iron and nickel. They have enormous energies of one billion electron volts up to at least a billion, billion electron volts. (See page 209). By comparison, the biggest man-made particle accelerators have produced energies of only about one hundred billion electron volts. Some primary cosmic ray particles make it to the ground but most of them collide with molecules of the upper atmosphere knocking out other particles called *secondary cosmic rays* many of which do reach the earth's surface. These secondary cosmic rays consist of electrons, muons, pions and other fragments of atoms and nuclei. These are the particles that produced the ionization Victor Hess observed aboard the *Boehmen.*

Some cosmic ray particles have such penetrating power as to pass through meters of lead or thousands of meters of water or rock. These are the particles with the greatest energy and highest velocity.

There are now many devices for detecting cosmic rays which were not available when Victor Hess made his epic ascensions. The detector he used was an ionization chamber with electroscope. The rate at which its leaves drop is related to the number of particles passing through its chamber per

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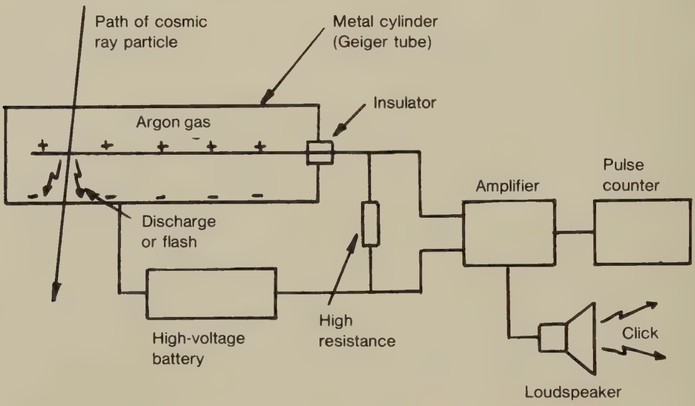
Note: The term *radioactivity* came into use long before the word "radio" was coined. Radioactivity implies that a substance such as radium emits or radiates particles or very short electromagnetic waves called gamma rays. It does not mean that the substance emits radio waves which are very long wavelength electromagnetic waves. However, the similarity of the words leaves them open to confusion.

minute or hour. Connecting the ionization chamber to an electronic amplifier can increase its sensitivity but an even greater improvement is provided by the Geiger-Mueller counter or Geiger counter invented by Hans Geiger and Walther Mueller of the University of Kiel in 1928.

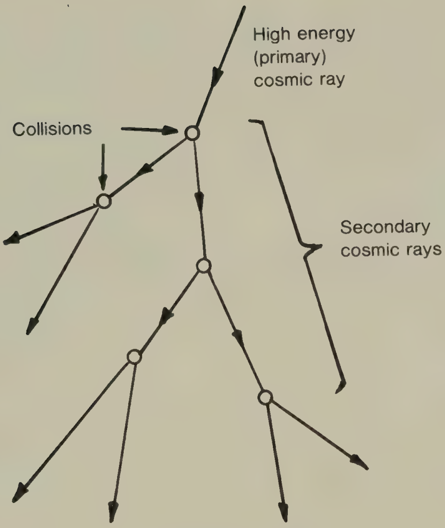
The *Geiger counter* is a remarkably simple yet effective device. A metal cylinder the size of a liter can is fitted with a central wire which is connected to the positive terminal of a high voltage battery. The cylinder or Geiger tube is filled with argon gas. When a particle passes through the cylinder it produces a trail of ions or charged particles and charges from the central wire can flow quickly along this trail to the cylinder like a miniature lightning flash. The electrical impulse of the flash is fed to an electronic amplifier and thence to a loudspeaker and a counter. For the transit of each particle there is a click of the loudspeaker and a pulse registered on the counter. To help restore the Geiger tube to its pre-particle condition as quickly as possible a small amount of ethyl alcohol vapor is included with the argon as a quenching agent.

To prevent all but the highest energy cosmic particles from activating the Geiger tube, it may be placed in a thick lead box, lowered in a deep lake or placed in a mine tunnel (in rock of low radioactivity) to shield it from the lower energy particles.

With Geiger tubes many new measurements became possible. For example, by connecting two Geiger tubes to a single counter arranged to record only essentially simultaneous pulses, particles passing through only one of the tubes are not counted while those passing through both are. This

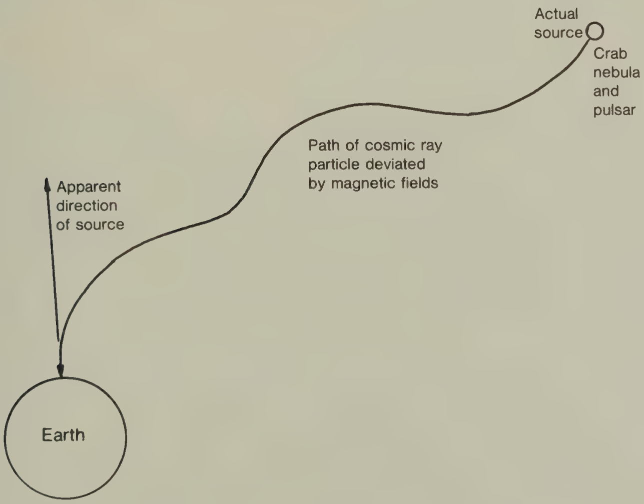


Cosmic ray particle passing through Geiger tube causes a click in the loudspeaker.



Cosmic rays

system, called a *coincidence counter,* provides a means for determining the direction of arrival of a particle and may be thought of as a simple *cosmic ray telescope.* Two Geiger tubes separated by a long distance will have a narrow angle of acceptance for coincidence counts while if placed close together the angle will be wider. However, there are situations where a coincidence may have a different interpretation.



A hypothetical cosmic ray path through space.

In 1933 at the University of Padua (where Galileo had taught and built his first telescopes) Bruno Rossi arranged three counters so no one particle could pass through all three. Yet he observed simultaneous pulses on all three providing evidence for the existence of showers of simultaneous particles. It was determined that a *shower* is produced by the collision of a high energy particle with an atom of the upper atmosphere resulting in many secondary particles.

Other devices are also in use for detecting cosmic rays. One of these is the *scintillation counter* in which the impact of a cosmic ray particle produces a visible flash on a fluorescent screen which can be recorded photographically or with a photocell.

A *charged particle* or *ionized particle* is produced when an electron is removed from an atomic particle, as by the nearby passage of a cosmic ray. The electron-deficient atomic particle is positively charged while the freed electron is negatively charged. A cosmic ray can ionize many atomic particles along its path, but if it collides head-on with an atomic nucleus it may be arrested while simultaneously knocking other particles out of the nucleus and transforming or transmuting the atom into a different element.

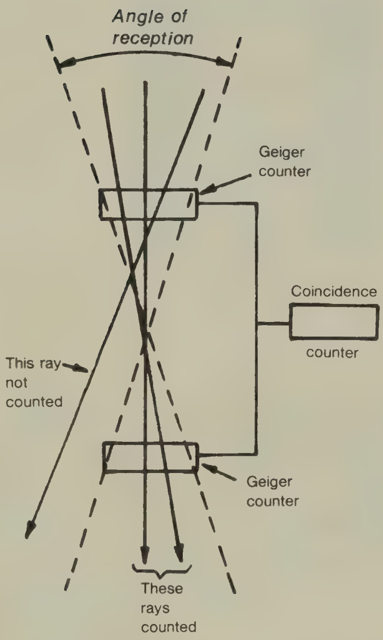
Studying cosmic rays in 1932, Carl D. Anderson of the California Institute of Technology found an electron with positive instead of negative charge. This positive electron, mentioned earlier on page 172, is now called a *positron.* A few years later Seth Neddermeyer and Carl Anderson discovered a particle, now known as a *muon,* with a mass intermediate between an electron and a proton (about 200 times the electron mass or one-ninth the proton mass). These were but the first of many new fundamental atomic particles discovered through studies of cosmic rays.

Cosmic ray detectors are often flown to great heights by unmanned balloons. If the earth had no atmosphere and no magnetic field, bombardment of the earth's surface by cosmic rays would be intense.

A cosmic ray (high energy) electron may interact with a magnetic field producing radio waves (synchrotron radiation). Or it may interact with a light photon producing a gamma ray (inverse Compton scattering). The radio and gamma rays we detect from remote parts of space may, thus, be indicators of the presence of cosmic rays in these locations. For example, it is believed that most of the galactic gamma ray background is produced by galactic cosmic rays (electrons) interacting with interstellar photons of our galaxy. The electron imparts some of its energy to the photon, decreasing the photon's wavelength into the gamma ray region.

In ordinary Compton scattering, named after Arthur Compton, an American physicist who discovered the effect in 1923, a photon impinging on an electron is deflected or scattered at a longer wavelength (lower energy) while imparting energy to the electron.

In a coincidence counter a particle must pass through both Geiger tubes to be counted. From this the direction of the particle can be inferred.

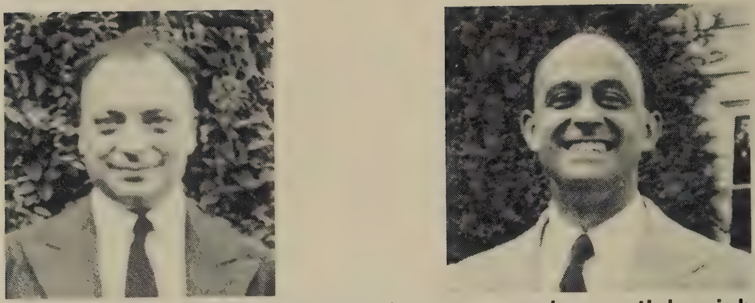


Observations of the most energetic (and least deviated) cosmic rays seem to indicate that more come from the plane of the Milky Way than elsewhere suggesting an origin in our galaxy.

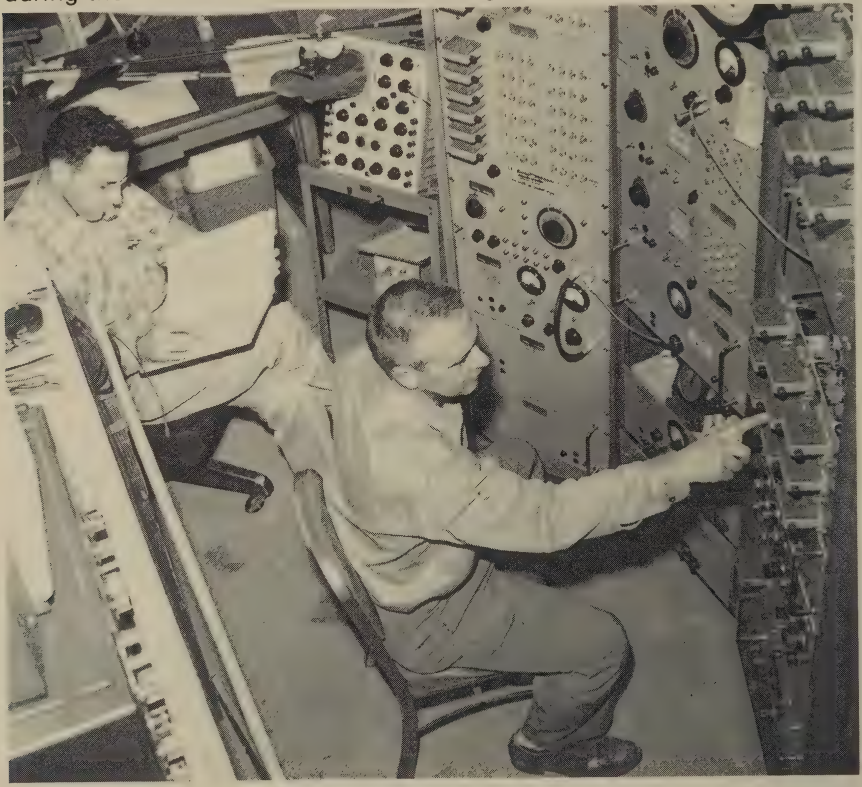
Neutrinos from Space

In addition to the cosmic ray particles we have discussed, all of which are charged, there is yet another particle, the *neutrino,* not usually thought of as a cosmic ray, which may be arriving in large numbers from the cosmos. The neutrino is a chargeless, virtually massless particle traveling at essentially the speed of light. Having no charge it is not deflected by magnetic fields and, accordingly, travels in a straight line. It can penetrate great thicknesses of matter. In fact, a neutrino should be able to pass completely through the earth with ease.

In the early 1930s Wolfgang Pauli suggested that a new nuclear particle might exist. By 1934, Enrico Fermi developed a theory for the new particle which he named the neutrino (Italian for "little neutral one") but because the neutrino has no charge and is essentially massless, it is very elusive and difficult to observe. It was not until 1956 that Clyde Cowan and Frederick Reines succeeded in detecting the neutrino in a laboratory experiment.

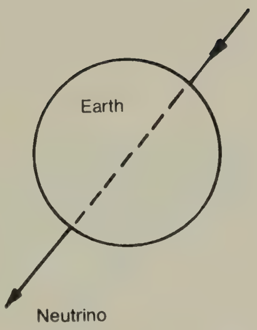


Wolfgang Pauli (left) suggested that a new nuclear particle might exist. Soon Enrico Fermi (right) developed a theory for the new particle which he named the "neutrino." (Photographs taken by Edward H. Kraus during the 1930s when both were working on the neutrino concept.)



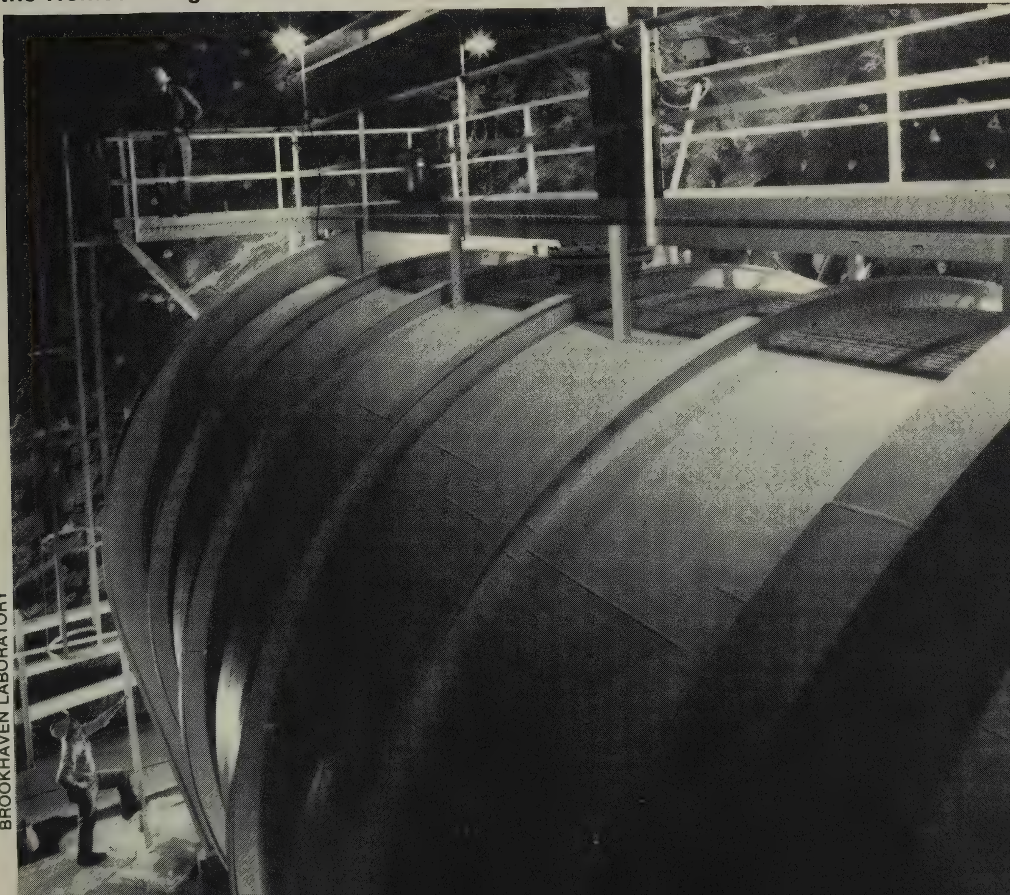
Frederick Reines (left) and Clyde L. Cowan, Jr. with the control equipment used in their first tentative observations of the neutrino at Hanford, Washington, in 1953. Their definitive detection of the neutrino was performed at Savannah River, Georgia, three years later. (Courtesy General Electric Co.)

A neutrino can penetrate the full diameter of the earth in less than a second and, squeezing its way between the atoms without hitting any, go merrily on its way. But a very occasional neutrino might get stopped if it makes a bulls-eye on an atomic nucleus. If this nucleus happens to belong to a chlorine atom in Raymond Davis' tank of cleaning fluid in the Homestake Gold Mine, it will get counted.

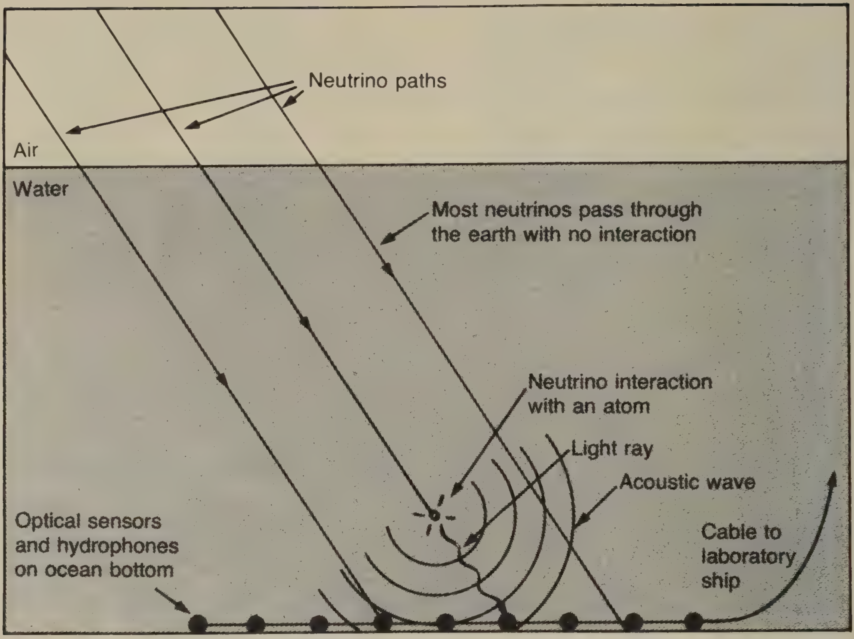


During the fusion of hydrogen into helium in a stellar core it is believed that neutrinos are produced in large numbers as a by-product of the reaction. The neutrinos travel freely through the star's interior and outward into space. If these neutrinos from a star could be detected it would provide astronomers experimental confirmation of their theories of how energy is generated deep inside the star. Light or other electromagnetic radiation can indicate what is taking place on a star's surface or in its atmosphere (or corona) but not what is happening deep inside, because the electromagnetic

Raymond Davis' tank of cleaning fluid 1500 meters underground in the Homestake gold mine for detecting neutrinos from the sun.



BROOKHAVEN LABORATORY


Neutrino paths
Air
Water
Most neutrinos pass through the earth with no interaction
Neutrino interaction with an atom
Light ray
Acoustic wave
Optical sensors and hydrophones on ocean bottom
Cable to laboratory ship

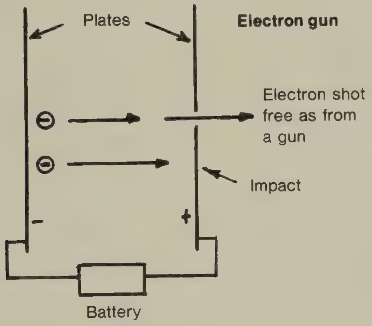
In the proposed Deep Underwater Muon and Neutrino Detection system the light flash and acoustic "ping" resulting from a neutrino interaction with the nucleus of an atom would be picked up by optical sensors and hydrophones (underwater microphones) deployed on the bottom of the ocean.

waves (or photons) can't penetrate the dense matter below the star's surface.

Because of its proximity, the sun is the best star on which to try a neutrino search, and in 1967 Raymond Davis, Jr., installed a huge tank 1500 meters deep in the Homestake Gold Mine at Lead, South Dakota to search for neutrinos from the sun. The tank contains 400 000 liters of perchloroethylene, a liquid used for cleaning clothes.

When a neutrino strikes a chlorine atom of the cleaning fluid it changes it into a radioactive argon atom. By periodically measuring the amount of radioactive argon produced the number of captured neutrinos can be determined. Thus far, the yield of neutrinos has been less than one-third that expected. The apparent failure to detect neutrinos from the sun in the numbers predicted has caused puzzlement among theorists and it is not known whether theories about the reactions in stellar cores need revision or whether the mechanism of neutrino capture is not well enough understood.

Frederick Reines, who with Clyde Cowan made the first laboratory detection of neutrinos in 1956, has proposed that a huge array of microphones on the ocean floor could act as a neutrino telescope for observing celestial sources beyond the sun. This could lead to a new science of neutrino astronomy. A Pacific Ocean site with flat, level floor is under consideration. It is northeast of the Hawaiian Islands at a depth of 500 meters. It is proposed to listen for the sound pulse or ping produced when a neutron makes a direct hit on the nucleus of an atom of the sea water. By recording the times at which each microphone detects the ping it should be possible to deduce the neutrino's direction of arrival.

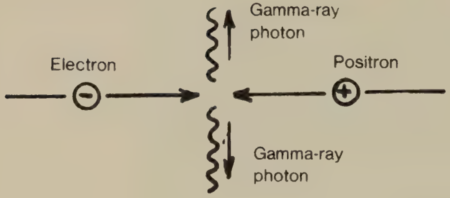


If an electron is released in the space between two metal plates to which a battery is connected, it will move toward the postively charged plate (to right), since it is repelled by the negative charges (on left plate) and attracted by the positive charges (on right plate). In moving between the plates the electron gains energy, like a rock falling from a height, and it will collide forceably with the right plate like a falling rock impacting the ground. However, if a hole is drilled in the plate the electron can pass through and continue on its way as though shot from a gun. Television receivers have guns of this type to fire electrons at a screen to produce the TV picture.

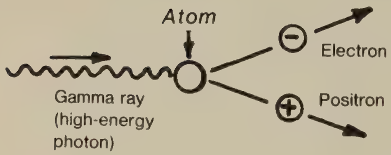
If the battery voltage applied is one volt, the electron, in moving between the plates, will acquire a velocity of 590 kilometers per second (over one million miles per hour). It is apparent that a small voltage can impart a high velocity to an electron. By analogy to the falling rock, the electron in "falling" through one volt is said to acquire an energy of *one electron volt.* Energies of cosmic ray electrons are enormously greater, and are measured in millions and billions of electron volts.

The *electron* is a tiny particle with the smallest unit of negative electric charge. Electrons are the carriers of electricity over wires in all of our electrical devices. The *proton* has a charge equal to that of the electron but it has a positive instead of negative charge and the proton is nearly two thousand times heavier. Muons and pions are particles with a mass between the electron and proton and of either positive or negative charge. (See page 261).

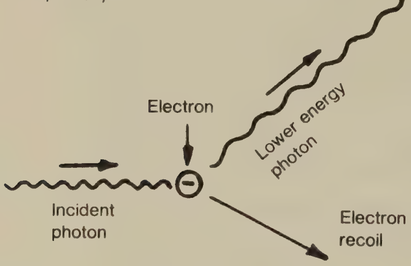
SOME PARTICLE-PARTICLE AND PARTICLE-PHOTON INTERACTIONS



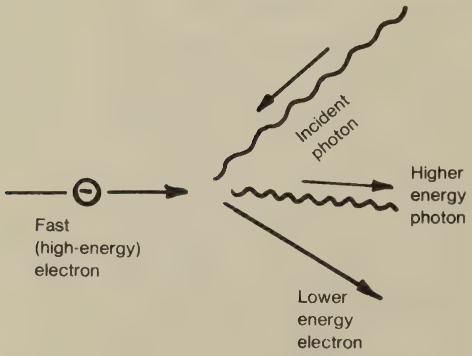
Matter into radiation. Annihilation of an electron-positron pair produces gamma-ray photons (511 000 electron volt line).



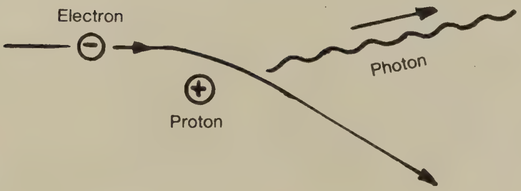
Radiation into matter. Photon transforms into an electron-positron pair on impact with atom. (Radiation into matter).



Compton scattering. Photon wavelength increased. Photon gives up some of its energy to electron. A Compton scattering event is a down-converter of the photon frequency.



Inverse Compton scattering. Photon wavelength decreased (light to x-ray or gamma ray). Electron gives up some of its energy to photon. An inverse Compton scattering event is an up-converter of photon frequency.



Bremsstrahlung. Free-free interaction of electron deflected by proton produces photon radiation. The electron leaving the interaction has less energy by the amount imparted to the photon. Typical radiation mechanism of an ionized hydrogen cloud.

Particle and Photon Interactions

Is the *photon* a particle? Electromagnetic waves are quantized into "packets" called photons. However, a true particle (even in vacuum) always travels at a speed which is less than that of light (300 000 kilometers per second) whereas photons, being electromagentic waves, always travel (in vacuum) at *exactly* the speed of light.

Gravity Waves from Space

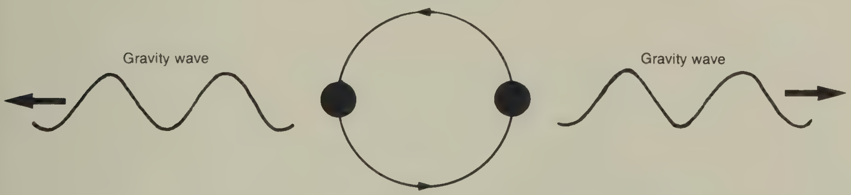
In addition to electromagnetic waves and atomic particles, gravity waves may be another courier of information from the cosmos.

Gravity is the force of attraction between two masses. It is the force which keeps the earth in its orbit around the sun and the force which binds us to the earth. What then is a gravity wave?

Any object, be it a golf ball or the earth, produces a gravitational attraction which is proportional to its mass, the larger the mass the larger the attraction. If a golf ball is suspended on a string and swings back and forth toward you and away, like a pendulum, it produces gravity waves in the sense that when it swings closer to you its gravitational effect is greater than when it swings farther away. Thus, its oscillation results in a variation of the gravitational attraction which fluctuates in a wave-like manner. For the golf ball, however, the strength of the wave is exceedingly small.

The motion of any object produces gravity waves so whenever you move you produce gravity waves; you are a gravity wave transmitter, albeit a very weak one.

To generate gravity waves of significant strength more massive objects are needed. Thus, for example, two stars, each as massive as our sun, revolving around each other like swinging partners in a square dance, will



Two stars revolving around each other, like swinging partners in a square dance, can send out gravity waves of substantial power.

send out gravity waves of substantial power.* Likewise, a star with nuclear fuel depleted, which collapses on itself into a pulsar or black hole, will radiate a strong pulse of gravity waves.

Although gravity waves are theoretically possible and searches for them have been in progress for some years, none have as yet been detected for sure.

Assuming that, as techniques are improved, gravity waves will be detected and, further, that it may be possible to generate sufficiently strong gravity waves under intelligent control to send messages via these waves, could gravity waves become a revolutionary new method for interstellar communication?

For a receiver we might use a device similar to the basic one developed by Professor Joseph Weber, pioneer gravity-wave scientist, of the University of Maryland, consisting of a large aluminum bar suspended at its mid-point and isolated from atmospheric and vibrational effects by enclosing it in a cushioned, evacuated tank. A passing gravitational wave tends to make the bar vibrate as though tapped by a small hammer. The vibration of the bar generates electrical signals in sensors attached to the bar and these signals are then amplified and recorded.

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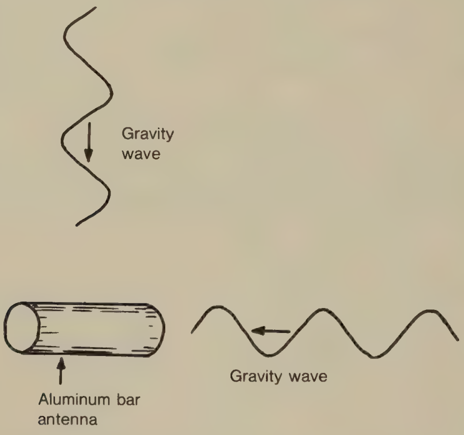
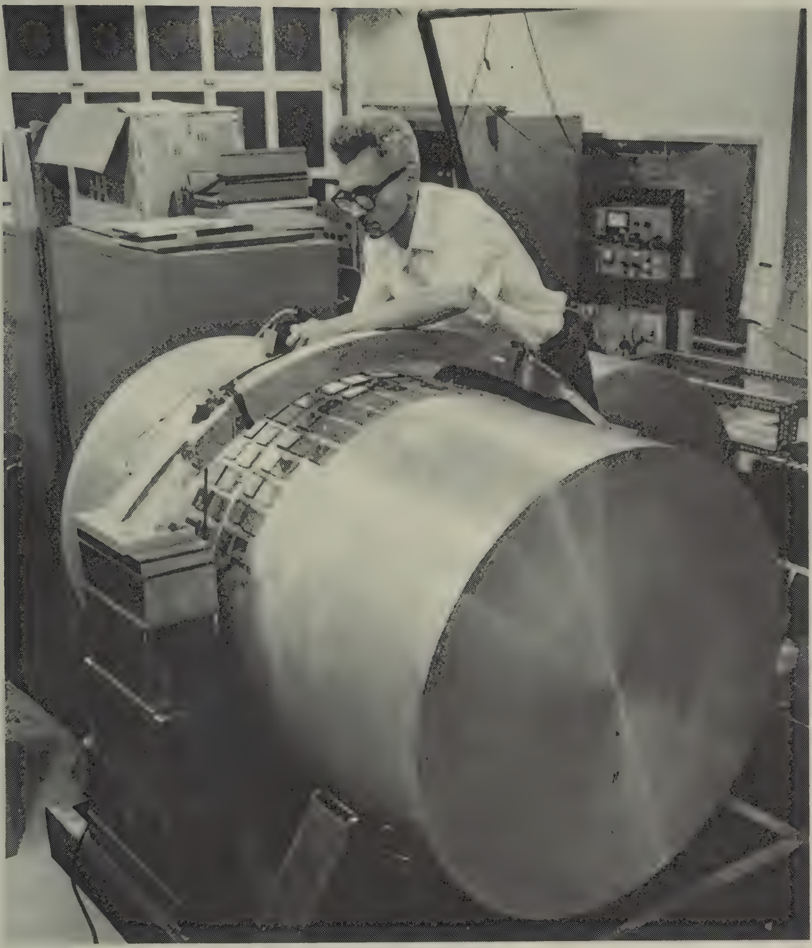
* The revolving stars constitute a gravitational *quadrupole.* By contrast, electromagnetic waves can radiate from electric charges oscillating along a straight wire constituting an electric *dipole.* Gravitational radiation, that is, gravity waves at a large distance from their origin and completely detached from it, cannot be of the dipole type but can only be of the quadrupole type because a dipole requires positive and negative poles whereas masses are only of one sign.

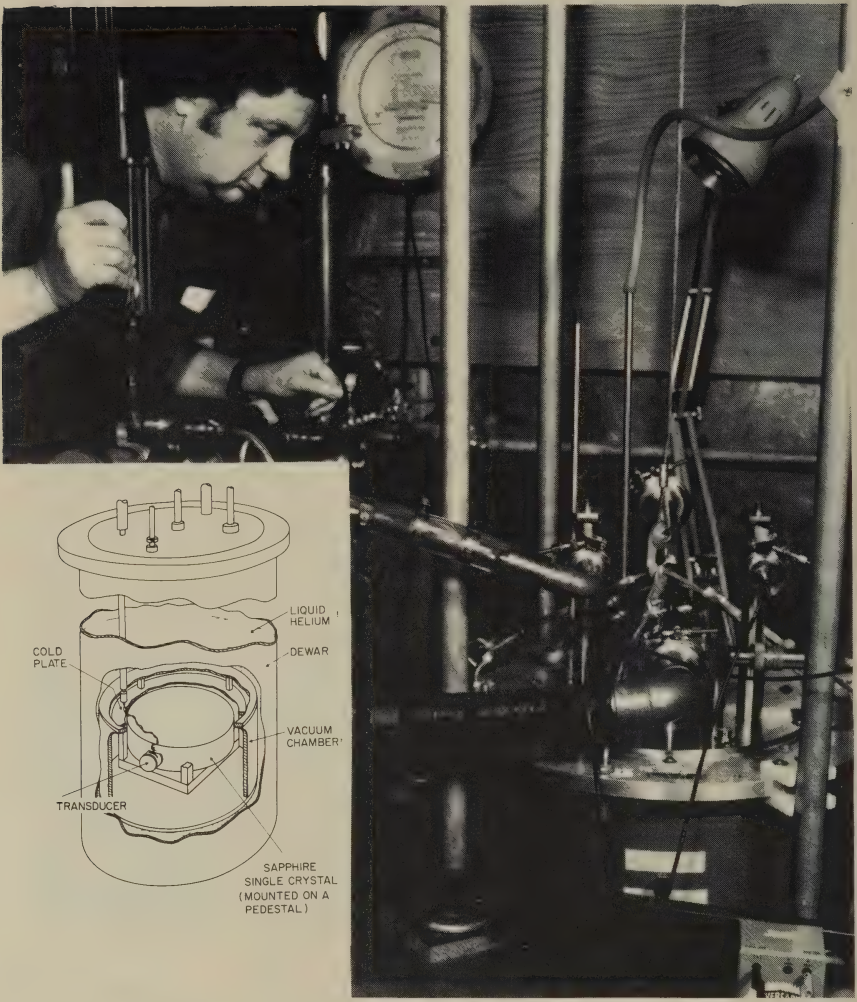


Weber-bar antenna for gravity waves. The bar responds more strongly to a wave approaching broadside (from top) than end on (from right).


UNIVERSITY OF MARYLAND

Professor Joseph Weber working on his aluminum bar gravity wave antenna. The small plates he is adjusting are the piezoelectric sensors. For gravity wave measurements the big aluminum bar is covered with a sound-proof air-tight enclosure from which the air is pumped out.

A number of groups are developing new and more sensitive gravity wave telescopes in the hope of detecting gravity waves. The sensitivity of the bar-like antenna system is proportional to its mass and its stiffness or "Q" and inversely proportional to the temperature. Therefore, the new antennas will be cooled to almost absolute zero and will be as massive and stiff as possible. Professor David Douglass of the University of Rochester is testing large, pure, single crystals of silicon and sapphire to use as his antennas because these show promise of having extremely large Q (that is,

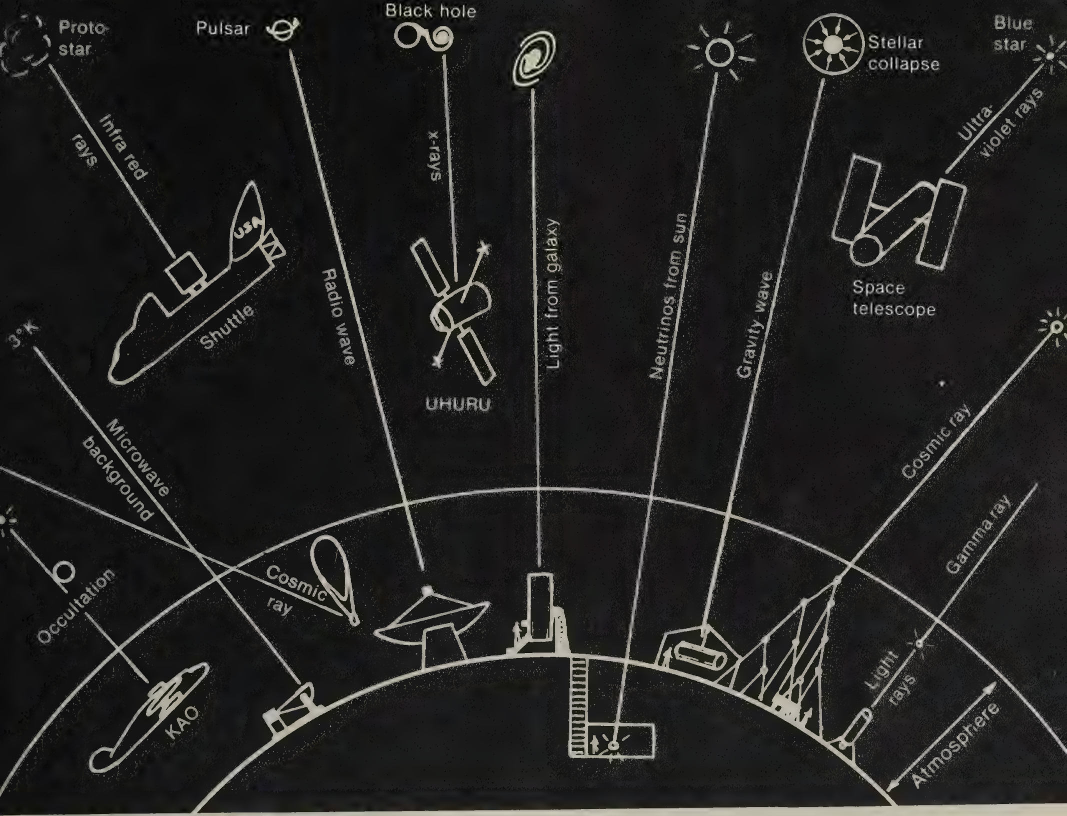


UNIVERSITY OF ROCHESTER

Professor David Douglass with evacuated low-temperature sapphire-crystal gravity wave antenna. Electrical signals from gravity waves are picked up from the crystal by sensor or transducer attached to it.

stiffness) which can result in higher sensitivity than obtained by using bars of softer material such as aluminum.

Although the exploration of space with gravity wave telescopes holds great promise, its use is yet to be determined. Man believes there are cosmic gravity pulses but he is still seeking them. Like James Thurber's "things that go thump in the night" mankind is looking for evidence of things that go thump in the universe.



Mankind's eyes and ears on the universe.

All Kinds of Telescopes

From gamma-ray and x-ray telescopes orbiting in space, optical telescopes on mountain tops, radio telescopes on secluded plains, gravity wave telescopes in vacuum tight enclosures inside buildings, to neutrino telescopes more than a kilometer underground, there is great diversity in type and location of the instruments astronomers have devised to probe the universe. But more bizarre and unusual may yet come.

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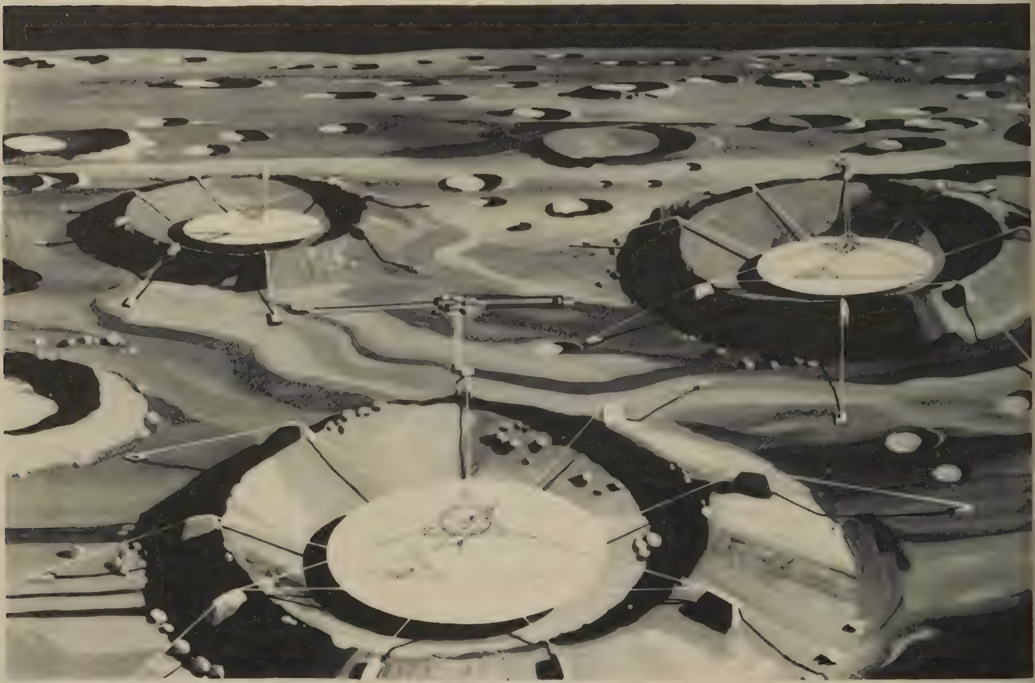
From the big monoliths of Stonehenge of 2000 B.C. to huge antennas to be built in craters on the back side of the moon by 2000 A.D., man's questing spirit has been roving the cosmos.



NASA

GREAT ADVENTURES TO COME

From Stonehenge to Antennas on the Moon

Astronomy's greatest value is that it lifts us above our self-centered attitudes and provides a true perspective of ourselves as dwellers on a small, fragile planet, a mere speck in a seemingly limitless universe. The questions astronomy raises about the universe, its origin, its destiny and whether we are its sole intelligent inhabitants, are some of the most basic and profound which we can ask. The exploration of the universe is an essential part of our development if we are to reach our full potential. How can we understand ourselves and our immediate problems if we don't understand something of our total environment, the cosmos in which we dwell?

Astronomy has already taught us much. But what of the future? What new things are in store? There are many exciting prospects.

The Space Telescope is just the first of many elaborate space observatories which can be put into orbit and serviced by the Space Shuttle. With large new optical telescopes in space it may be possible for the first time to photograph planets circling other stars. Plans are underway by NASA for many space astronomy missions during the coming years.

Other observatories may be built on the moon. A radio observatory on the back side of the moon would have the advantage of low gravity, shielding from terrestrial interference and the absence of an atmosphere and ionosphere. A long wavelength radio observatory is already in lunar orbit to take advantage of the shielding by the moon. (See page 150).

Probes to the planets will greatly increase our knowledge of the solar system. In particular, what we learn about Mars (with its less dense atmosphere) and Venus (with its much denser atmosphere) can help immensely in understanding atmospheric phenomena and weather patterns on the earth (with its intermediate density atmosphere).

Gravity wave observations are still in a primitive state, much as radio waves were a century ago after Maxwell postulated their existence but before Hertz generated and measured any.

Another new astronomy may deal with pulses, not the regular, repetitive ones sent out by a pulsar, but enormous single pulses produced when a star explodes and/or collapses into a pulsar or black hole.

When an atomic bomb explodes there is a blinding flash of light accompanied by a pulse of intense electromagnetic radiation from gamma and x-rays to radio waves. This burst of radiation is very powerful, yet it is as nothing compared to explosions or catastrophic events of the cosmos. There are frequent explosions on the sun which would dwarf a Hiroshima blast. Yet these are miniscule relative to the explosion of a whole star. Not only electromagnetic waves but also gravity waves, neutrinos and cosmic rays may be generated in prodigious amounts. Even over vast astronomical distances the events may be observable from the earth.

Theory says there ought to be a short pulse, lasting only a second or so, at the very beginning of the outburst. Then may come the main outburst itself lasting minutes, hours or days. This is what the Chinese astrologer saw in 1054 A.D. and what astronomers, optical and radio, have observed for other stars and objects on a number of occasions. The initial short pulse has, however, been rarely if ever observed and a new astronomy for detecting these pulses may well be one of the future's most important developments. What is needed are telescopes which monitor the entire sky continuously at many wavelengths from gamma rays to radio. The Vela satellites are, in fact, doing just that for gamma rays.

If a gravity wave pulse could be detected that occurred simultaneously with a visual flash or an x-ray, gamma-ray or radio pulse, this could provide direct experimental evidence that gravity waves travel at light speed.

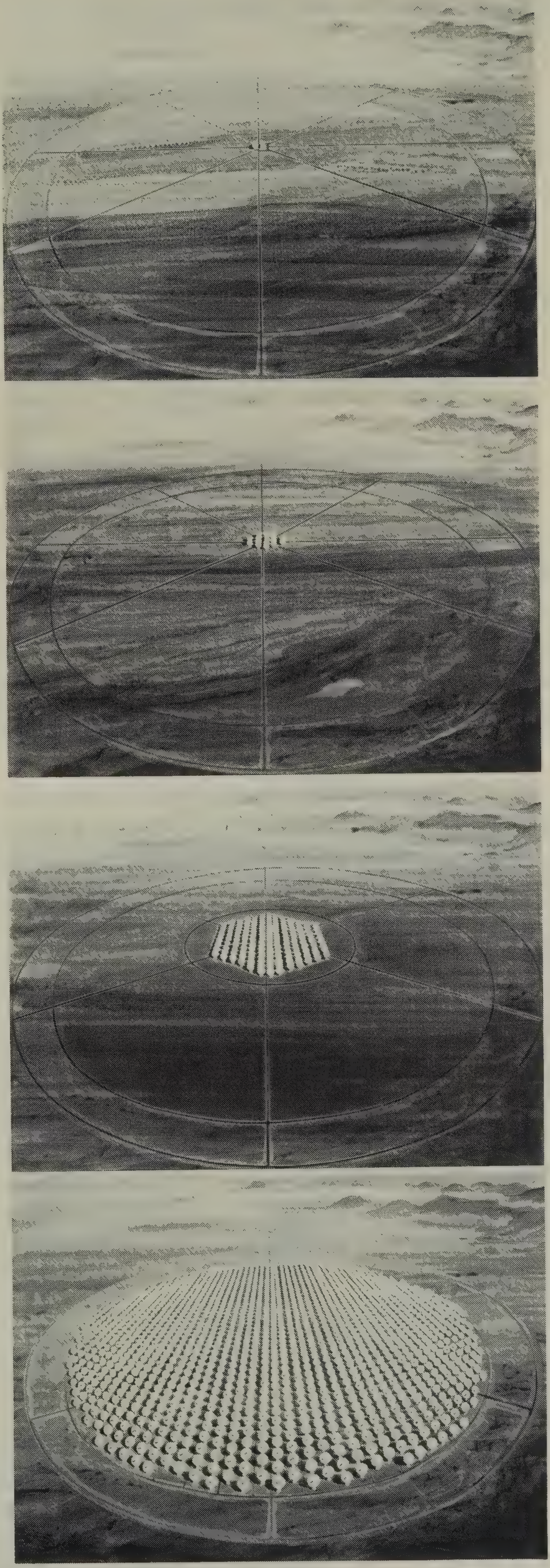
Project Cyclops and the Search for Intelligent Life Beyond the Earth

As man's knowledge of the universe grows there is a question which is perhaps more pertinent than any other. Are we alone? Are we unique, a real cosmic curiosity? Or are there intelligent beings elsewhere? In fact, is there any life at all beyond the earth? The answers to these questions are of profound significance and the Search for Extra-Terrestrial Intelligence (SETI) is becoming an increasingly important phase of astronomy.

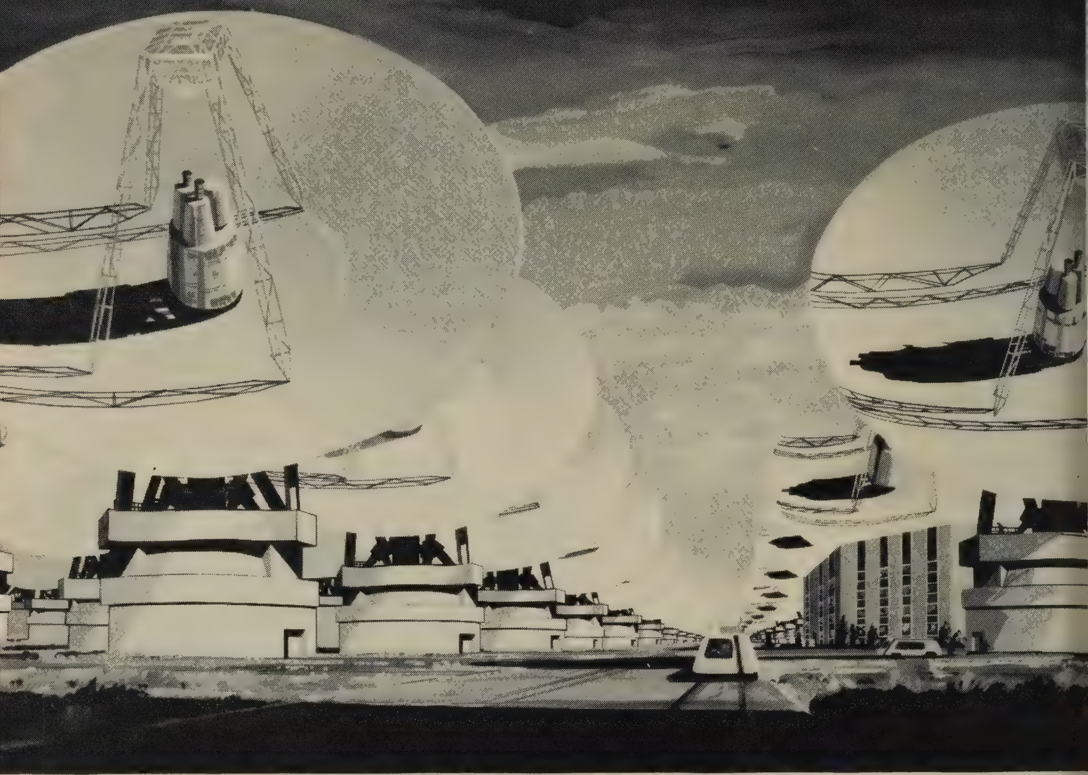
Lee DuBridge, former president of the California Institute of Technology puts it this way: "Either we are alone or we are not. Either way is mind boggling."

In 1971 the National Aeronautics Space Administration sponsored a study called "Project Cyclops" (after the mythical one-eyed giant) which was organized by Bernard Oliver and John Billingham. The stated objective of Project Cyclops was "to assess what would be required in hardware, manpower, time and funding to mount a realistic effort, using present (or near-term future) state-of-the-art techniques, aimed at detecting the existence of extra-terrestrial (extra solar system) intelligent life." The term "realistic effort" was used in the context of one which has a high probability of success. Obviously, before any hardware such as a huge antenna is constructed, there must be much thought, study and planning. One plan envisions an array of a thousand 100-meter diameter antennas connected to operate like a single gigantic antenna.

But where should we search and on what wavelength or channel? The sun is the only star we know which has planets. Additionally, one of these plants (the earth) has life. The sun is a yellow dwarf star of the G type so it would be reasonable, in the absence of other information, to begin searches of sun-like stars. (See chart on page 53).

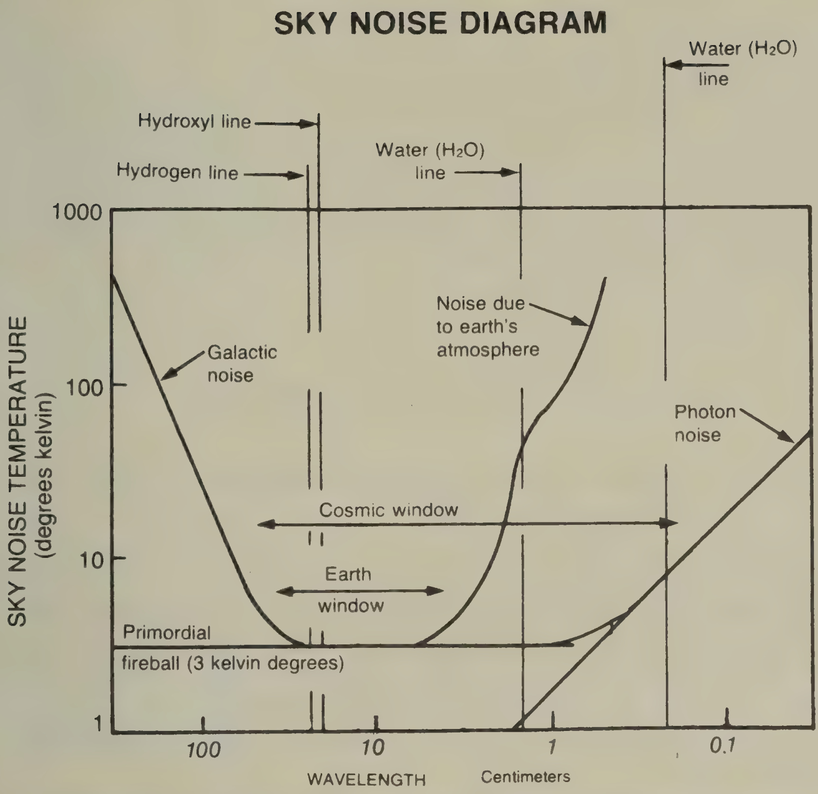


The proposed Cyclops system would begin with a single antenna (top) and grow by steps as necessary. The complete Cyclops array (bottom view) would consist of one thousand 100-meter diameter antennas and would cover an area 3 kilometers in diameter. The antennas would be connected together to act as a single big antenna. (Courtesy of NASA).



100-meter diameter Cyclops antennas. NASA

Receiving antenna placed in orbit by the Space Shuttle. NASA



Searches for signals are best made in the sky-noise windows.

The Water Holes

Are there some wavelengths that would be better for searches than others? Yes, ones for which natural radiation from the galaxy will be a minimum and for which waves will travel with least absorption. Wavelengths between a few millimeters and 30 centimeters would appear to be best. (See Sky Noise Diagram).

The hydrogen (H) line is at 21 centimeters and the hydroxyl radical (OH) line at 18 centimeters. Combining H and OH makes H_2O (water) so the wavelengths between 18 and 21 centimeters are often referred to as the "water hole" alluding to the fact that galactic civilizations might gather at these wavelengths to talk with each other like animals of different species gather around an African water hole to drink.

There are also 2 and 14 millimeter lines of the water molecule (H_20) and these might be regarded as bracketing another "water hole".

Might extraterrestrial civilizations use signalling methods of an entirely different type? By 2500 A.D. will our present communication techniques seem as primitive as smoke signals? Have all the kinds of rays or waves been found or are some new ones yet to be discovered? No one knows but we would be very presumptuous to think that we have discovered them all. Predictions have often been made that there was little fundamentally new to be discovered only to be shattered by later developments.

Broadband or Narrowband?

What kind of signal might one expect from a distant civilization? If it is sent intentionally it will most likely be narrow band (ideally a single wavelength, a pure "color" if we could see it, as contrasted to a band or range of wavelengths) because such a signal travels furthest for a given power. This is the kind of signal we use for Morse code telegraphy. Voice signals require a wider band of wavelengths and TV still wider.

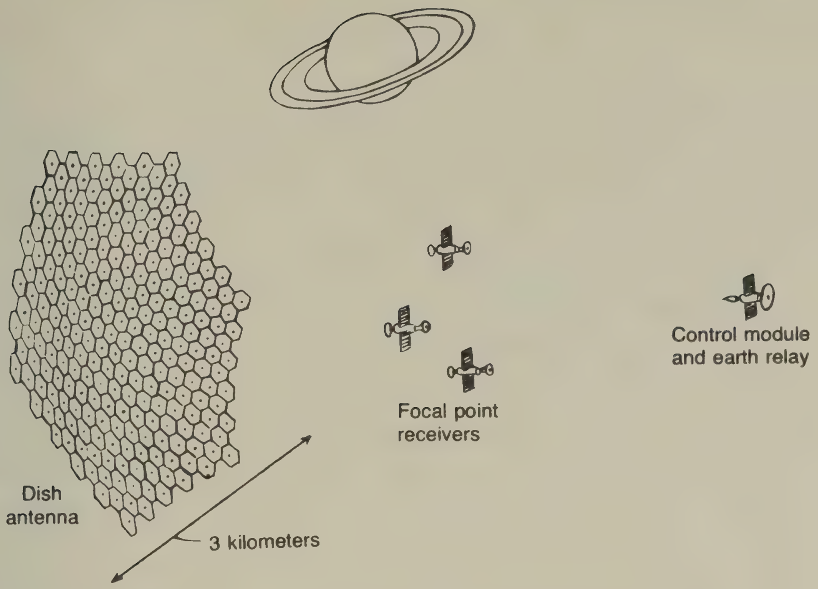
If you turn on your radio at 3 A.M., when only a few stations are on the air, and tune your receiver you hear a hissing noise, like escaping steam, all across the band until you tune in a station and the noise gives way to speech or music.

As you were tuning, and searching, you were listening to BROADBAND noise. It was the same anywhere you tuned. When you tuned in the station, you were listening to a NARROWBAND signal carrying information or "intelligence." You only heard this station when you were tuned to a specific wavelength.

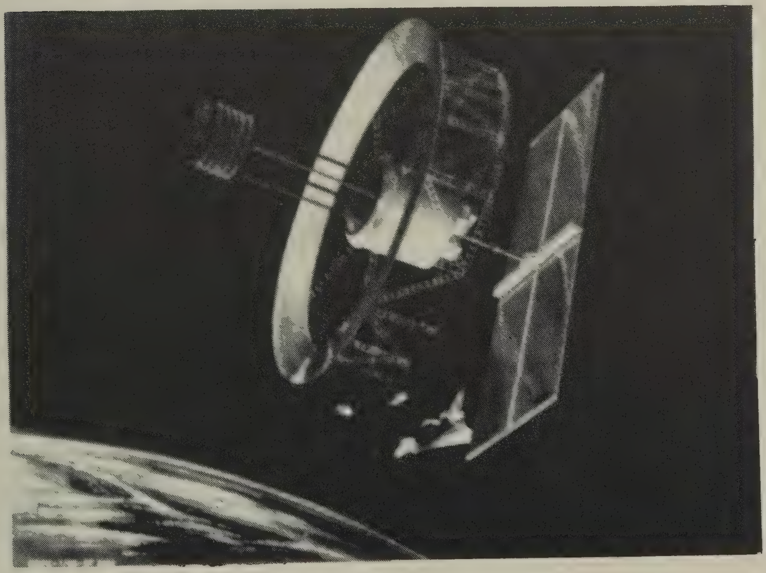
Why does a broadcast station transmit a narrowband instead of a broadband signal? Because it can be heard farther and more clearly if it concentrates its power in a narrow band of wavelengths instead of spreading it out over many wavelengths.

Before World War I, in the early days of radio (it was called "wireless" then), high voltage spark discharges were used for transmitting code signals but even with high power the stations couldn't transmit far because

100-meter diameter super-optical space telescope contemplated for future orbital observations. Planets of other stars should be observable with this telescope. The 100-meter diameter mirror is not a continuous solid surface, the inner portion being omitted, making the instrument a partially-filled aperture telescope. (Courtesy of NASA)



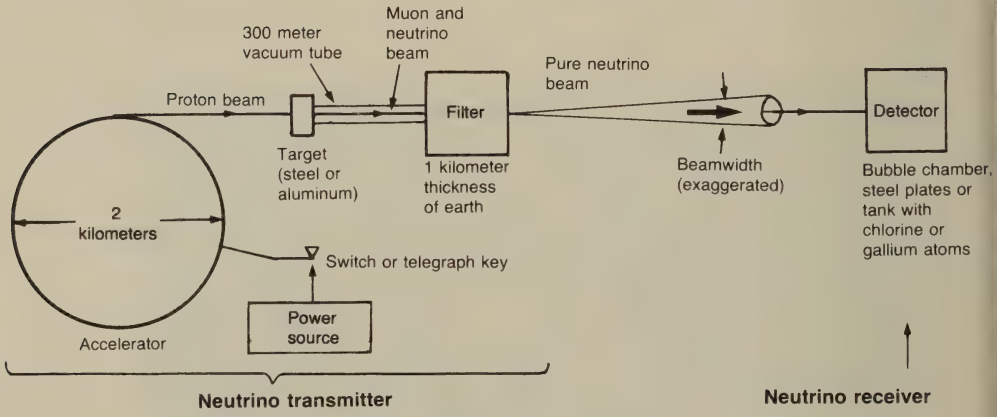
Proposed Soviet radio telescope with which 3-dimensional or holographic pictures could be obtained of all observable objects in the universe. Planets the size of the earth could be detected from their thermal radiation alone at distances of 100 light-years and planets like Jupiter at 1000 light-years. Two units, each like the one shown, would be deployed near Saturn's orbit with a third unit near the earth.



the spark generated a broadband signal (which could be heard all across the dial). After World War I, when vacuum tube transmitters came into general use, it was possible to generate much narrower band signals which could be heard only at one spot on the receiver dial. These signals carried much farther and spark transmitters soon became obsolete.

The significance of this is that an extraterrestrial technological civilization would, no doubt, use a narrowband signal for its transmissions. It might even make it so narrow that it couldn't even carry speech or music but only the slow dots and dashes of a cosmic Morse code because this could go still farther. It makes more sense (if you want to be found) to send Morse code signals very slowly (carrying but little information) rather than a voice signal (with more information) which is never heard by anyone. (A television signal is even broader band than speech and would have still less range).

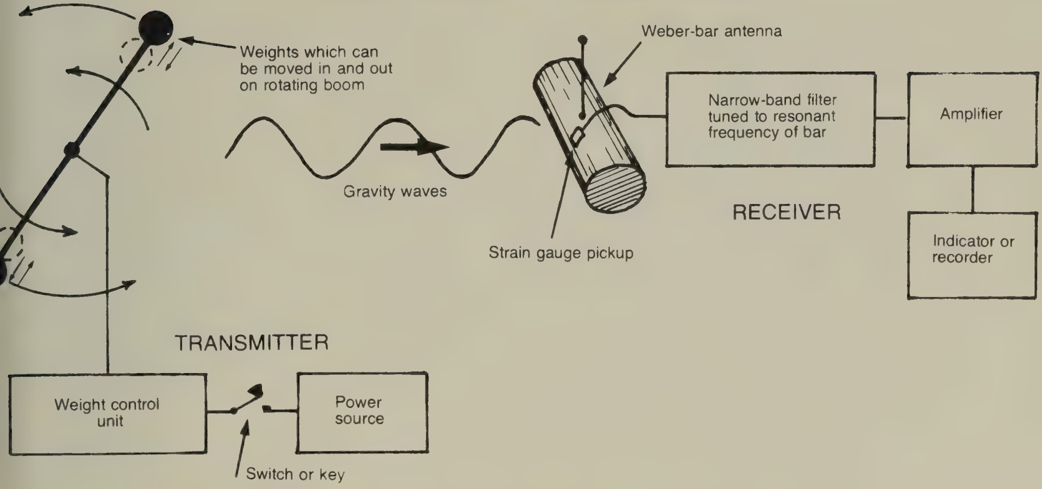
This explains why most searches for extraterrestrial intelligence are done with very narrowband receivers. Since, however, the particular wavelength an extraterrestrial society might use is uncertain, many narrow bands or channels are usually searched simultaneously. The channels could be searched one at a time but this would take much longer. The multi-



A Neutrino Communication System

A neutrino "communication system". We are just approaching a capability when, with large particle accelerators, we can generate copious numbers of neutrinos, but we are still far from developing an interstellar neutrino communication system. Yet, other civilizations may have passed this point long ago.

A gravity wave communication system



Arrangement which could be used for gravity wave communication if sensitivity could be increased sufficiently. Rotating boom idles with weights out. With weights pulled in, the boom speeds up sending out gravity waves at frequency to which massive aluminum bar antenna is tuned.

channel receiver is analagous to an array of 100s of receivers each tuned to a different channel in the hope that someday on one channel the long-sought-for signal might be heard.

Even at a slow sending rate of dots or dashes, it is possible to send pictures, as in a wire-photo, but it might take a long time, measured in days, to send just one picture over interstellar distances. Ordinary television pictures (at a rate of many pictures per second) are also sent with dots and dashes but they must be sent at a very high rate (millions per second) and this requires a broader bandwidth. Thus, for a given power, a slow rate of sending information is appropriate if you want your signals to go as far as possible whereas a high rate of sending information or data will reduce the distance at which your signals can be detected. Whether the dots and dashes are sent at a slow or fast rate, the waves carrying them always travel through empty space at the same velocity of 300 000 kilometers per second.

Time and Space

If we were to detect signals from intelligent beings on a planet revolving around a distant star is it likely that they would be more advanced than we are? Yes, it is. Our evolution from primitive life forms has taken billions of years, yet we have possessed the technological capability to conduct a search for scarcely a decade. We are a very young civilization; we are just emerging. Unless the beings on the distant planet evolved at precisely the same rate as we over billions of years, which is most unlikely, they will either be less advanced, in which case we will be unaware of them and they of us, or they will be more advanced, perhaps millions of years more advanced. Eons ago, as an emerging civilization, they may have grappled with many of the problems we are now facing — population, energy, pollution, war — and solved them, perhaps by closed-loop, long range planning. Even without understanding any message the civilization may send, the mere knowledge of its existence suggests that another society has attained a high technological level *and* survived. This could give us encouragement that we too can solve our problems.

On the other hand, if after years or centuries of listening and searching we hear no signals, it could mean one of several things:

(1) that there is no intelligent life elsewhere
(2) that if there is it has not reached or passed our level of technological development.
(3) that the technological civilizations that have evolved do not choose to transmit, or, a most sobering prospect
(4) that when a civilization develops an advanced technology it destroys itself; it is a terminal type. Are technological civilizations unable to plan ahead wisely; do problems like pollution and war bring them to an early end? If so, they may appropriately be called technological civilizations but not really too intelligent.

Suppose signals are detected from a civilization which is 1000 light-years away. The signals will be 1000 years old when we receive them. They will be relics of the past and, like terrestrial archaeologists who excavate artifacts of ancient Greek or Egyptian civilizations, we will be cosmic archaeologists intercepting an ''electromagnetic time capsule'' which has been speeding across the depths of space for ages. If we do eventually understand the message the signal conveys and choose to transmit a reply it will take another 1000 years before it is received by the distant civilization. There will be a 2000 year delay built into our ''conversation.''

We will need to do some very long range thinking and planning. It will be a new experience to learn of a civilization from which we are isolated in *both* time and space. The civilization will not be one which lived long ago on the banks of the Nile but may be one which lived on a planet so distant that what we learn of it now was broadcast before the Nile civilization was born.

Ronald Bracewell of Stanford University has suggested that advanced extraterrestrial civilizations may have launched automated probes like our Pioneers and Voyagers, except much more sophisticated and able to travel vastly farther out into space until they approach other stars. From these vantage points they gather data and periodically radio the information back. Such ventures would require some very long range planning because a trip between stars could take tens of thousands of years.

Nikolai Kardashev, Josef Shklovsky and others of the Soviet Academy of Sciences have proposed an interferometer radio telescope with a base line 20 times our distance from the sun with antennas at about the orbit of Saturn. With such a system it is possible in principle to make three-dimensional or holographic figures of the entire universe. This means that the distance, size and shape of every observable object in the universe could be determined. This bold proposal indicates that radio astronomers are still far from the end of their tether. Furthermore, such a system could be used to advantage for the detection of extra-terrestrial civilizations.

Harnessing a Black Hole

Harnessing a black hole may sound a bit futuristic but the famous text "Gravitation" by Charles Misner, Kip Thorne and John Wheeler (W.H. Freeman) includes a hypothetical example about how an advanced civilizaton could construct a rigid platform around a black hole and build a city on the platform.

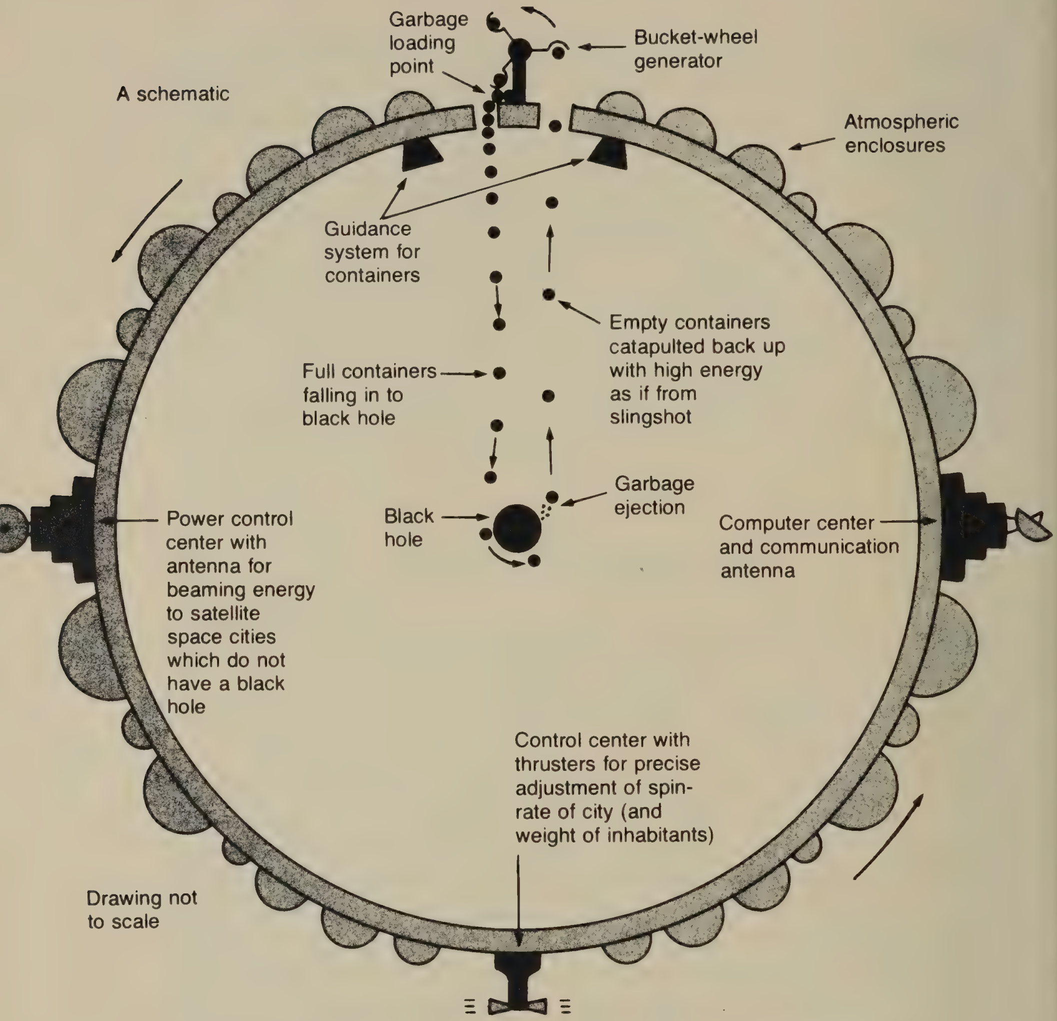
The discussion goes on to say that every day garbage trucks carry a million tons of garbage collected from all over the city to a dump point where the garbage goes into special containers which are then dropped one after the other down toward the black hole at the center of the city. The container is dragged by the black hole's strong gravity into a vortice-like whirlpool swirling around the black hole, spiralling inward toward the critical distance. When the container reaches a certain "ejection point" it dumps its load and as the garbage goes on into the hole the empty container recoils and is catapaulted back up where it is caught by a giant bucket-studded flywheel. The container's energy spins the flywheel and this in turn runs a generator. With a succession of garbage containers falling in and flying back up, the generator provides a steady power supply for the city.

To quote from Misner, Thorne and Wheeler,

"Not only can the inhabitants of the city use the black hole to convert the entire rest mass of their garbage into the kinetic energy of the vehicle (or container) and hence into electrical power but they can also convert some of the mass of the black hole into electrical power!"

Now a million tons (mass) of garbage a day converted into energy in this way would produce more than a billion trillion watts of power or nearly a billion times the present-day power production of the entire world. Many

Poweropolis: A Black Hole City


Garbage loading point
Bucket-wheel generator
A schematic
Atmospheric enclosures
Guidance system for containers
Empty containers catapulted back up with high energy as if from slingshot
Full containers falling in to black hole
Garbage ejection
Black hole
Power control center with antenna for beaming energy to satellite space cities which do not have a black hole
Computer center and communication antenna
Control center with thrusters for precise adjustment of spin-rate of city (and weight of inhabitants)
Drawing not to scale

Poweropolis is a hypothetical city of 200,000,000 built on a framework rotating around a black hole. By dumping their garbage into the black hole, the inhabitants generate a billion times the energy per person now available per person in the U.S.

details involving much research would need to be worked out before this fanciful scheme could be converted to reality, but who knows, it may already be used by an advanced civilization somewhere in the universe.

We have considered many devices and systems but the most unusual and bizarre may belong to the future, for, as John A. Wheeler, the father of the black hole, has said,

"The greatest discoveries are yet to come."

The Solar System Signature: How Our Solar System Would Appear to an Observer at a Distant Star

We have considered how we might detect other civilizations and how they might appear to us. Let us turn the tables and consider how we might appear to them.

Although the sun is the largest object and the principal source of radiation from the solar system, two of the planets, Jupiter and the earth, also contribute.

An overall view of the radiation from the solar system as it might appear from a distant star is shown by the accompanying **Solar System Signature** or spectrum.

At the lower left of the "signature" is a small peak at a few kilohertz (10^3 to 10^4 hertz) due to leakage from the earth's open wire electric power distribution lines. Higher harmonics of the 60 hertz currents penetrate the earth's ionosphere and in the magnetosphere or Van Allen region are amplified as much as 1000-fold by wave-particle interactions.

A larger peak at 200 kilohertz (1500 meters wavelength) is from radio waves generated by fast particles in the Van Allen belts. The power level fluctuates, being associated at times with auroral (northern or southern) light activity. The total power from this radiation source sometimes amounts to a billion watts. The peak would be higher if it weren't for the fact that the radiation is spread out over a relatively wide bandwidth of a couple hundred kilohertz. The ionosphere between the Van Allen belts and the earth acts like a metallic shield and prevents this strong radiation from penetrating down to the earth. If if were not for this shielding this Van Allen noise would severely jam broadcasts in the long wave radio band.

Still higher in frequency, around 20 megahertz (15 meters wavelength), Jupiter makes itself heard due to radiation from fast electrons in its magnetosphere. The radiation appears to be initiated or controlled by Jupiter's small inner moon Io. The total power of this radiation at its maximum is a billion watts, the same as the earth's Van Allen radiation, but the power per unit bandwidth (chart vertical scale) is less because the bandwidth is greater.

At about this frequency the radio emission from the sun becomes significant even during the relatively quiet periods between sunspot maxima which occur every 11 years. During a spot maximum the radiation may be a thousand times greater and much in excess of the Jupiter radio radiation, and even enough to mask TV signals from the earth as discussed in the next paragraph.

Next on the "signature" are three tall spikes near 200 megahertz (1.5 meters wavelength), 400 megahertz (75 centimeters wavelength) and 2 gigahertz (15 centimeters wavelength) due to man-made signals from television, military early-warning radar and planetary radar stations. The bandwidths are narrow so the power per unit bandwidth is large. All of these stations use antennas which increase the effective power in certain directions. The solid part of each spike shows the power level if the power is radiated uniformly in all directions while the dashed extension indicates the increase in effective power due to the antenna.

The television station spike is *not* due to the modulation which produces the picture but to the very narrow bandwidth carrier (less than 1 hertz bandwidth) which is the backbone of the signal. Sullivan, Brown and Wetherhill have pointed out that although an Arecibo system might detect a television carrier at a distance of a light-year or so, "ten thousand times more sensitivity would be required to obtain program material."

The most intense signals from the earth are from planetary radar stations which bounce radio waves off the moon, Venus and Mars. Such stations are located at Arecibo in Puerto Rico, Jodrell Bank in England, Goldstone in California and elsewhere. These radar stations may transmit with very narrow bandwidth. Since much of the effective power results from the large antenna used (dashed part of the spike), this means that the direction in which a strong signal is transmitted is very limited in angular extent, as in a very narrow searchlight beam, so even though the signal is strong the chance of it being picked up by an observer at another star is very small.

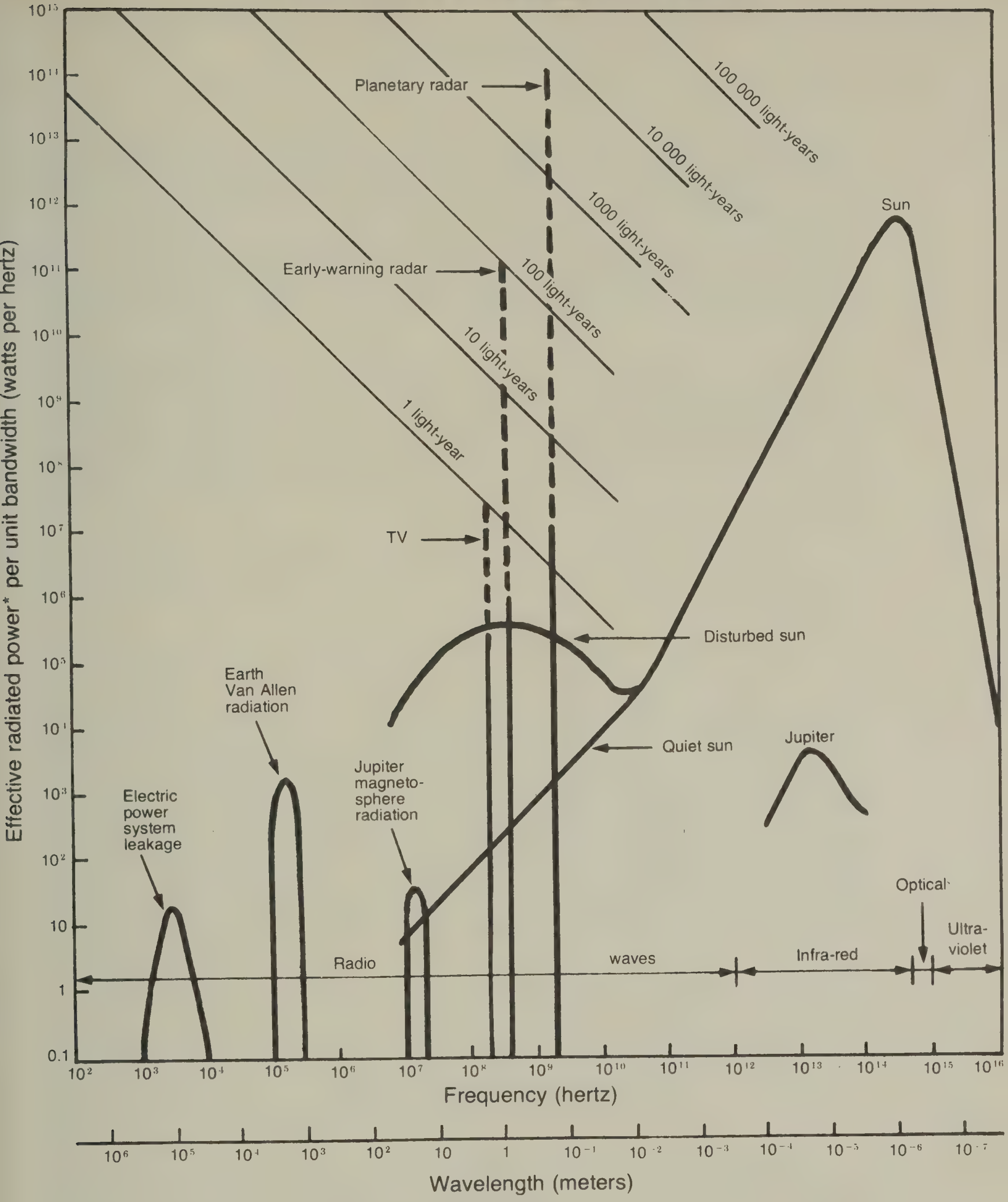
The world's AM broadcasting stations, including the most powerful ones of several million watts in Saudi Arabia, are confined in coverage to the earth by the ionosphere, and while the FM stations' frequencies are high enough to penetrate the ionosphere, they are not powerful enough to be contenders.

As we go to still higher frequencies on the "signature" the radio, infrared, optical and ultra-violet radiation from the sun becomes dominant.

Now suppose you live on a planet revolving around a star 1000 light-years from our sun. At this distance the solar system out to the orbit of the planet Pluto subtends an angle like that of a penny seen from a distance of 15 kilometers so when you point your radio telescope at the sun you also have the planets in the beam and observe the whole solar system as a single entity. Suppose your radio telescope has 100 times the sensitivity of Arecibo (such as a large orbiting telescope now under consideration) and also you have a sizable optical telescope (the sun would be too faint to be seen by the unaided eye at 1000 light-years).

Referring to the "signature" you could detect everything projecting above the line marked 1000 light-years or the sun and a planetary radar. Things below (shaded) would be too weak, or as communication engineers would say, "buried in the noise". If you were at a distance of 10 000 light-years only the sun could be detected (above line marked 10 000 light-years).

THE SOLAR SYSTEM SIGNATURE



*Effective radiated power (ERP) equals radiated power times antenna gain (if any).

A distant observer 1000 light-years from the solar system could detect one of the earth's planetary radars and also the sun. At 100 light-years the observer might also just marginally detect one of the earth's early-warning radars and at 1 light-year do the same for the carrier of a TV station but would not be aware of any sound or picture. (See text for assumptions involved).

On the other hand, at 100 light-years an early warning radar station could just be detected but even at the relatively close-up distance of one light-year a TV station would not yet be detectable, and the Van Allen, Jupiter and earth power line radiation would also be too weak.

Although our discussion has been greatly oversimplifed*, it gives some idea of how far radiation could be detected for different solar system sources.

Suppose that at your distant star you had detected a planetary radar signal from the earth, would you associate it with a technological civilization in the solar system? Perhaps not, unless you could study it for some time. If the radar were being beamed at one of the sun's planets, it is not likely you would have this opportunity because as the planet moves the beam would wander off from your direction.

We have discussed how communication at 1000 light-years could be possible with technology we now have or soon may have. But what kind of communication?

We have assumed a receiver response time of 10 seconds so it would take about a minute for a dot and longer for a dash. This means it could take an hour or so just to say "Hello". There could be no speech, no music, no TV, just slow dots and dashes — a rudimentary Morse code communication like Marconi's first three dots across the Atlantic in 1901. *And* there would also be a 1000 year delay so a good question would be whether the civilization which sent the signals still existed. The signals could only tell you that there *was* a technological civilization in the solar system 1000 years before. Could the signals, you might ask, be artifacts of a vanished society — electromagnetic relics from antiquity rushing through space at the speed of light?

A Search for Brains

The brain is unique in that, as far as we know, it has the highest concentration of information (data content per liter of volume) existing anywhere in the universe, the concentration being vastly greater than even in the most micro-miniaturized electronic computer. One of the most unique things about a planet like the earth is its conscious, intelligent life and its high concentration of information content in things like living human brains. Are there life forms elsewhere with an even higher information concentration? A Search for ExtraTerrestrial Intelligence may be considered as a search for those places in the universe where there is a high concentration of information.

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* We have assumed that the receiver bandwidth matches that of the transmitter or source and that the bandwidth-time-constant product of the receiver is unity. Other factors affecting the results are sky background temperature, wavelength and signal-to-noise ratio (assumed equal to 10). With somewhat different assumptions, ranges could easily change by a factor of 10 or more.

Bernard Oliver has commented:

"The greatest miracle we have before us is the fact that within a few billion years the universe has converted a part of itself into conciousness and that part can now contemplate the universe which began it".

The Voyager Messages

On August 20, 1977, a Voyager spacecraft was launched from Cape Canaveral on a scouting trip which carried it past Jupiter in 1979. Traveling on past Saturn and toward Uranus, it will ultimately leave the solar system forever. A phonograph record attached to the space craft carries messages from the earth to possible remote space-faring civilizations which, a million years hence, might encounter the Voyager drifting like a derelict raft on a cosmic ocean. One of the messages is from President Jimmy Carter and reads in part:

"This is a present from a small distant world, a token of our sounds, our science, our images, our music, our thoughts and our feelings. We are attempting to survive our time so we may live into yours. We hope someday, having solved the problems we face, to join a community of galactic civilizations. This record represents our hope and our determination, and our good will in a vast and awesome universe."

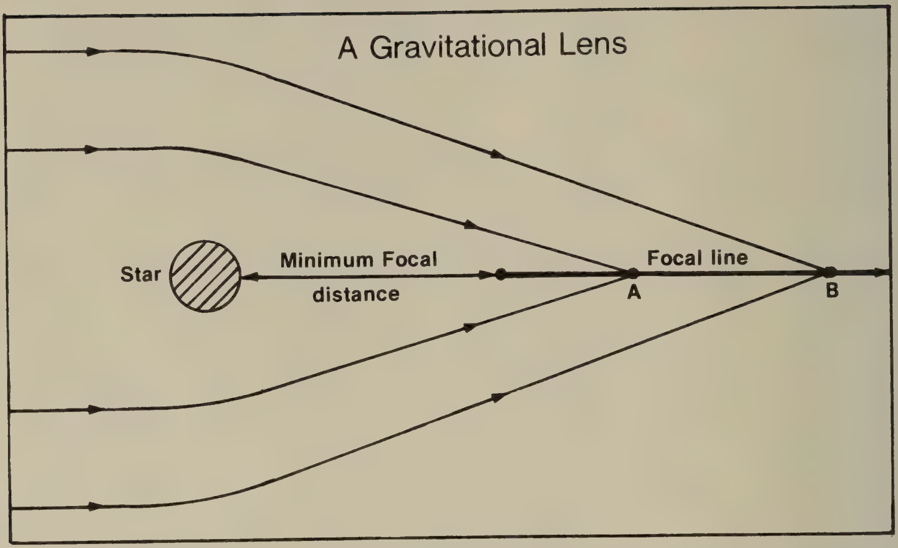
Space city. (Courtesy of NASA).

Discovery Dates

Date	Radiation	Discovered or first detected by
1800	Infra-red rays	Herschel
1801	Ultra-violet rays	Ritter
1888	Radio waves	Hertz
1895	X-rays	Roentgen
1896	Gamma-rays	Becquerel
1912	Cosmic rays	Hess
1956	Neutrinos	Cowan and Reines

Cosmic Calendar

15 billion BC	Universe began (BIG BANG)
10 billion BC	Our galaxy formed
5 billion BC	Solar system formed
2 million BC	Homo sapiens emerged
5000 BC	Writing invented
2000 BC	First calendars
200 BC	Eratosthenes. First determination of earth's diameter
150 BC	Hipparchus. First comprehensive star chart
1610 AD	Galileo. First optical telescope
1888 AD	Hertz produced radio waves
1901 AD	Marconi spans Atlantic by radio
1930 AD	Jansky. First radio telescope
1957 AD	Sputnik I
1965 AD	3 degree remnant of BIG BANG measured
1967 AD	Discovery of pulsars
1969 AD	First man on the moon
1973 AD	OQ172. Telescopes reach almost to "edge" of universe
1976 AD	Viking lands on Mars



Dixon, COSMIC SEARCH

The amplification at A and B is the same but finer detail (or greater resolution) is obtained at B.

Using the Sun to Amplify Radio Waves

When a radio wave passes near a massive object such as a star, its direction of travel is bent slightly toward the star. This bending is caused by the gravitational field of the star. If the radio wave is traveling directly toward the star, then it will be bent around it equally on all sides, and brought to a focus at some point behind the star. The star may be said to act like a lens in this case. If a receiver were located at this focal point, it would receive a highly amplified version of the original wave and hence could detect much weaker and more distant waves.

This amplification effect was originally pointed out by Albert Einstein in 1936, and was recently explored in more detail by Von R. Eshleman of Stanford University.* The amount of amplification is directly proportional to both the mass of the star and the frequency of the radio signal. For example, the Sun would give an amplification factor of 10 million at a frequency of 300 gigahertz (1 millimeter wavelength).

Actually, there is no single focal "point." Rather, there is a focal "line" that begins at some minimum distance behind the star, and continues radially outward to infinity. Any point along that line gives the same amplification factor. The minimum distance is inversely proportional to the mass of the object, and directly proportional to the square of its diameter. Unfortunately, this minimum distance is extremely large, which means the receiver would have to be located very remotely. For the Sun, the minimum distance is far outside the solar system, being about 15 times farther out than the planet Pluto.

**Science,* Sept. 1979.

PRACTICAL THINGS TO KNOW AND DO

Astronomy for the Amateur

What can an amateur see or hear of the cosmos with simple, inexpensive equipment? More than you might think. The huge telescopes of big observatories are not required to observe many fascinating, beautiful and mysterious things. An amateur can use both optical and radio telescopes and, instead of just reading about it, learn more through his own observations.

Much can be gleaned from the sky with the unaided eye, while giving one a kinship to all the astronomers before Galileo. The constellations can be located and identified. The changing positions of the moon, Mercury, Venus, Mars, Jupiter and Saturn can be followed. The Milky Way and some star clusters may be observed. There are also eclipses of the moon and sun and occulations of stars by the moon to be noted. Comets are exciting objects when they appear. Meteors, fireballs and artificial satellites provide more rapid movements to watch but you may be surprised at the number of high-flying aircraft you will spot. Counting meteors and recording their direction and length of trail will keep you busy during a meteor shower.

Camping out under the stars, you can watch the grand parade of the constellations from east to west across the sky. The sky on a clear, dark night is an awe-inspiring sight which has held a fascination since time immemorial.

An interesting experiment is to start watching the sky at evening twilight and see if you can detect any planets or stars. At first only Venus may be seen (if it is following the sun) or Jupiter (if it is up) and some of the brightest stars, such as Arcturus, Vega and Capella. Then, as the sky darkens other fainter stars will appear. Identifying these before entire constellations appear is good practice.

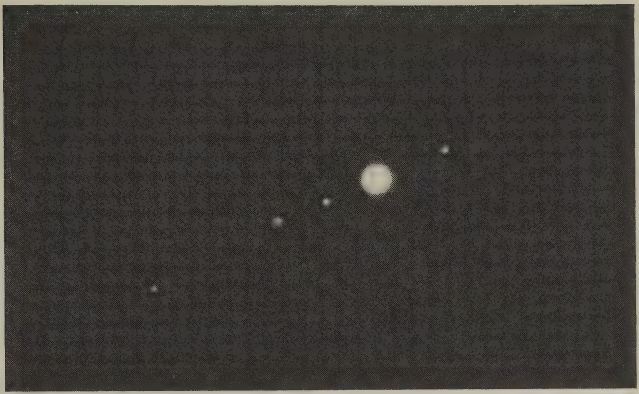
Or you can try locating Venus in broad daylight. It is never more than about three hours ahead of or behind the sun, and if you know how many degrees it should be from the sun, careful scrutiny may reveal it. (1 hour equals 15 degrees at the equator).

Comet Ikeya-Seki, November 1, 1965. 5:07 A.M. 60 second exposure on SS film from Gold Mountain, Japan with Nikon F camera by T. Yokota.

Comets are like "dirty snowballs", the core of the comet consisting of frozen water and other gases. As the comet approaches the sun, the solar heat vaporizes some of the material of the core which then streams out from the core and away from the sun forming the tail of the comet.

Spots on the sun can be observed and their day-to-day progress across the disc noted by projecting the sun's image with binoculars or a telescope as suggested in the sketch. Direct viewing with binoculars or telescope is also possible but only with proper filters and the exercise of extreme precaution because of possible harm to the eye.

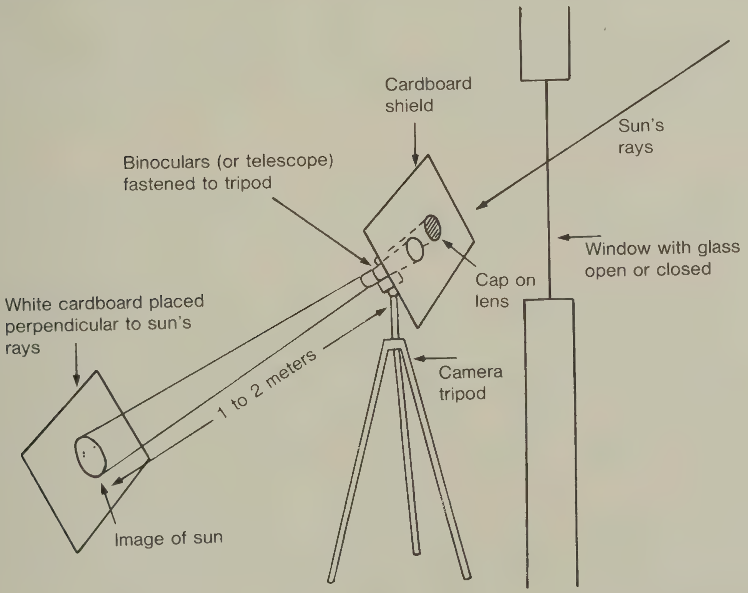
As discussed earlier the number of sun spots varies with an 11-year cycle. The strength of radio emission from the sun is related to the sun spots and if you have a radio telescope, as described later in this section, you can correlate the strength of the solar radio emission with the number and size of spots on the sun. Spots were at a maximum about 1935, 1946, 1957, 1968



Jupiter and moons. A miniature solar system. September 11, 1977. 4 second exposure on GAF 200 film from Mt. Pinos, California, with Celestron 14-inch telescope by Steve Reed. The order of Jupiter's moons are, left to right, 4, 3, 1, 2. 1 is the innermost and 4 the outermost.

and 1979 and it is expected that they will again reach a maximum about 1990. The maximum in 1957, which coincided with the International Geophysical Year, is the highest on record.

The study of sun spots dates back to Galileo's day. The most thorough early study and documentation of sun spots was by Christopher Scheiner, a German Jesuit astronomer and mathematician, who made detailed drawings of spots for many years in the period 1610 to 1630. These drawings


Cardboard shield
Sun's rays
Binoculars (or telescope) fastened to tripod
Window with glass open or closed
Cap on lens
White cardboard placed perpendicular to sun's rays
1 to 2 meters
Camera tripod
Image of sun

Method of observing sun's image and noting sun spots. With binoculars one lens should be capped to avoid a double image.

show the day by day progression of spots across the sun's disc and allow a precise determination of the solar rotation rate.

With a small telescope or even a pair of good binoculars you will be following in Galileo's footsteps and discover much more of interest. Craters on the moon, satellites of Jupiter, the Andromeda galaxy, star clusters and nebulas will come into view. Larger telescopes will reveal even more.

An interesting exercise is to observe the moons of Jupiter nightly, if possible, and sketch their positions as Galileo did in 1610 (see page 34).

Another exercise is to locate Uranus. Although it can be seen with the unaided eye under good conditions it is faint. Having a finite disc, Uranus shines with a steady light that distinguishes it from a star which twinkles. Some of the brighter asteroids, or minor planets, between Mars and Jupiter can also be located.

The more serious amateur can systematically observe any of the numerous variable stars, comparing them to standard or reference stars, to determine by how much they change and in what length of time. The American Association of Variable Star Observers (AAVSO) coordinates observations by amateurs.

Astronomical photography in color as well as black and white is a challenging field. With filters to admit only particular atomic lines, such as the Balmer alpha line of hydrogen, unique photographs can be taken of the sun. With special film and techniques you can extend the photography into the infra-red and ultra-violet. With prism attachments the spectra of stars can be seen and photographed.

Many telescopes of all sizes are available for the amateur. Kits are also sold which enable the amateur to build his own telescope and even grind his own optics. There are many books and magazines to assist (see references).

How many stars can you see? Assuming that the unaided eye can reach the 7th magnitude, it can detect about 14 000 stars in the entire sky (both the northern and southern hemispheres). At any one time no more than about half the sky can be seen by an earthbound observer so no more than about 7000 stars can be detected on a good night without a telescope. The scale of magnitude, used for specifying the brightness of stars, is in steps of 2.51-fold brightness change per magnitude, or 100-fold change in brightness for a step of 5 magnitudes ($2.51^5 = 100$), a *decrease* in magnitude corresponding to an *increase* in brightness. Thus, a 2nd magnitude star is 100 times *brighter* (100 times more power received) than a 7th magnitude star and a 12th magnitude star is 100 times *fainter* than a 7th magnitude star. A star 100 times brighter than 2nd magnitude would be of magnitude -3. The brightest star in the sky, other than the sun, is

Sirius of magnitude −1.5. The magnitude of the sun is about −27.

The accompanying table lists the approximate number of stars in the sky to various limiting magnitudes.

NUMBER OF STARS AS A FUNCTION OF MAGNITUDE

Magnitude	Number of stars
2	40
5	1500
7	14 000
10	300 000
14	14 000 000
17	150 000 000
20	1 000 000 000

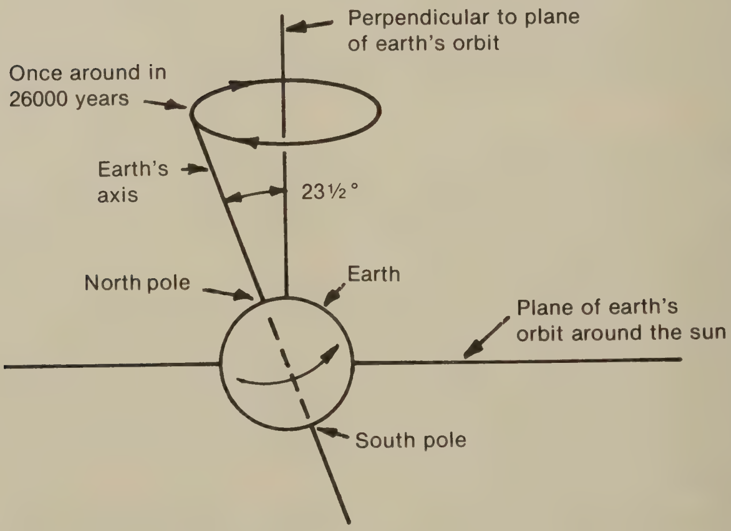
If 14 000 stars can be detected with the unaided eye how many can be observed with a 75 millimeter telescope? Assuming a pupil diameter of 3 millimeters for the eye the telescope is 25 times (=75/3) the pupil diameter and therefore it has 25 squared or 625 times the light gathering area or sensitivity. A factor of 625 corresponds to 7 magnitudes (=2.5 log 625). Thus, the 75 millimeter telescope should increase the limiting (visual) magnitude from 7 to 14 and according to the table this makes 14 million stars detectable.

The position of a star in the sky is usually specified in terms of its *right ascension* (R.A.) and *declination* (Dec.). Declination is always measured in degrees but right ascension is usually expressed in hours, minutes, and seconds of sidereal time.

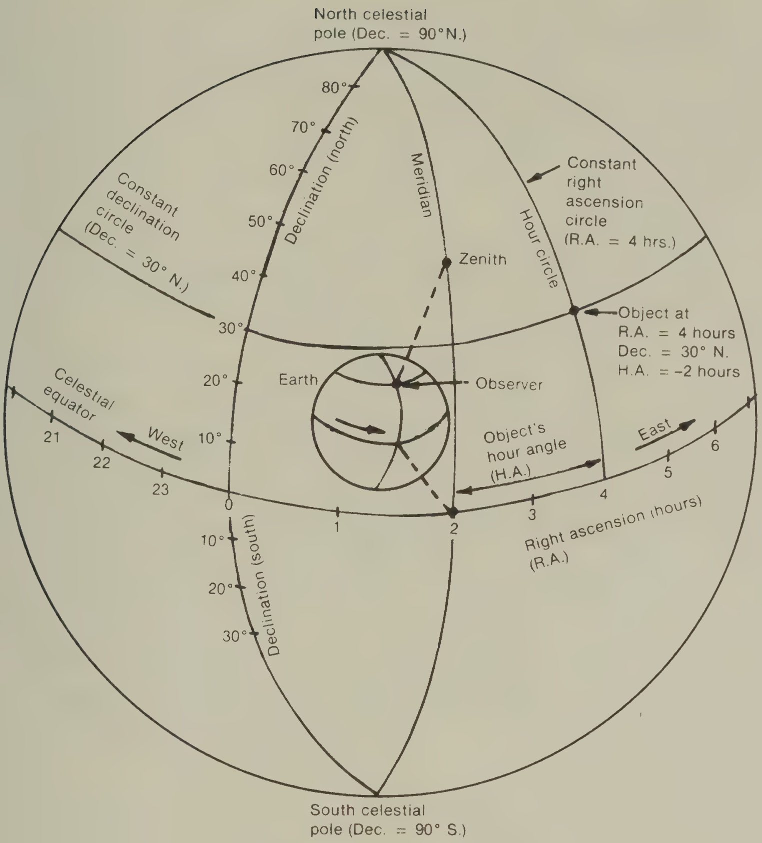
Imagine that the latitude and longitude grid of the earth is projected on the sky or celestial sphere. Then the circles of latitude correspond to circles of constant declination ranging from the *north celestial pole* (90° N. Dec.) to the *south celestial pole* (90° S. Dec.). The earth's equator projected on the celestial sphere is called the *celestial equator.* For an observer at 40° N. latitude as at Columbus, Ohio, the zenith (point in the sky directly overhead) has a declination of 40° N.

The earth's circles of longitude projected on the sky correspond to circles of constant right ascension with zero point located in the constellation Pisces. Right ascension increases eastward up to 24 hours right ascension. The starting point is called the *vernal equinox.* It is at the intersection of the celestial equator (or plane of the earth's equator) and the plane of the earth's orbit (or plane of the ecliptic) which the northbound sun passes in the spring (about March 21). Opposite the vernal equinox is the *autumnal equinox* which the southbound sun passes in the fall (about September 22). The autumnal equinox has a right ascension of 12 hours.

Because the earth's axis precesses slowly, like that of a spining top, the celestial coordinate grid of right ascension and declination creeps slowly across the sky going through a full cycle in about 26 000 years or at a rate of about 1/100 second per day. Therefore, to be explicit it is necessary to specify the date to which the right ascension and declination refer. This date is called the *epoch* and any atlas or table with star positions should give the epoch to which the positions apply. The precession is small enough, however, that it amounts to only about 2.5 minutes of right ascension in 50 years for a star at the celestial equator (0° Dec.) although more or less for stars away from the equator. The declination change in 50 years amounts to ¼° or less. Thus, an atlas or table of epoch within 50 years of the date of use may suffice, without corrections, for approximate settings. The epoch for the year 1950 usually written 1950.0, to indicate that it refers to the start of the year 1950, is in common use at present but many newer tables being published use an epoch 2000.0.


Perpendicular to plane of earth's orbit
Once around in 26000 years
Earth's axis
23½°
North pole
Earth
Plane of earth's orbit around the sun
South pole

Precession of the earth's axis.


North celestial pole (Dec. = 90°N.)
80°
70°
60°
50°
40°
30°
20°
10°
Declination (north)
Meridian
Constant right ascension circle (R.A. = 4 hrs.)
Hour circle
Constant declination circle (Dec. = 30° N.)
Zenith
Object at R.A. = 4 hours Dec. = 30° N. H.A. = -2 hours
Earth
Observer
Celestial equator
West
East
Object's hour angle (H.A.)
21
22
23
0
1
2
3
4
5
6
Right ascension (hours) (R.A.)
10°
20°
30°
Declination (south)
South celestial pole (Dec. = 90° S.)

Celestial coordinates of right ascension and declination and their relation to the earth's coordinates of longitude and latitude.

For small telescopes an equatorial mounting is convenient because turning the telescope on its axes moves it in right ascension and declination and once an object has been centered in the field of view it can be kept there by turning the telescope on its polar or right ascension axis at the rate of 15° per hour in a direction opposite to that in which the earth turns. If a clock drive is available the telescope can be turned automatically and it is said that the telescope tracks the object.

The (constant) right ascension circle through the zenith (point overhead) and the celestial poles is called the *meridian.* The (constant) right ascension circle through an object in the sky is called the object's *hour circle.* The arc of the celestial equator between the object's hour circle and the meridian is the object's *hour angle* (H.A.). It increases with time, being negative to the east before the object transits or crosses the meridian and positive or to the west after it transits.

Consider an object in the sky at a right ascension of 4 hours and a declination of 30° N. At the moment of observing suppose that the right ascension of the meridian is 2 hours. Then the hour angle is −2 hours (H.A. = R.A. of meridian — R.A. of object = 2 — 4 = −2).

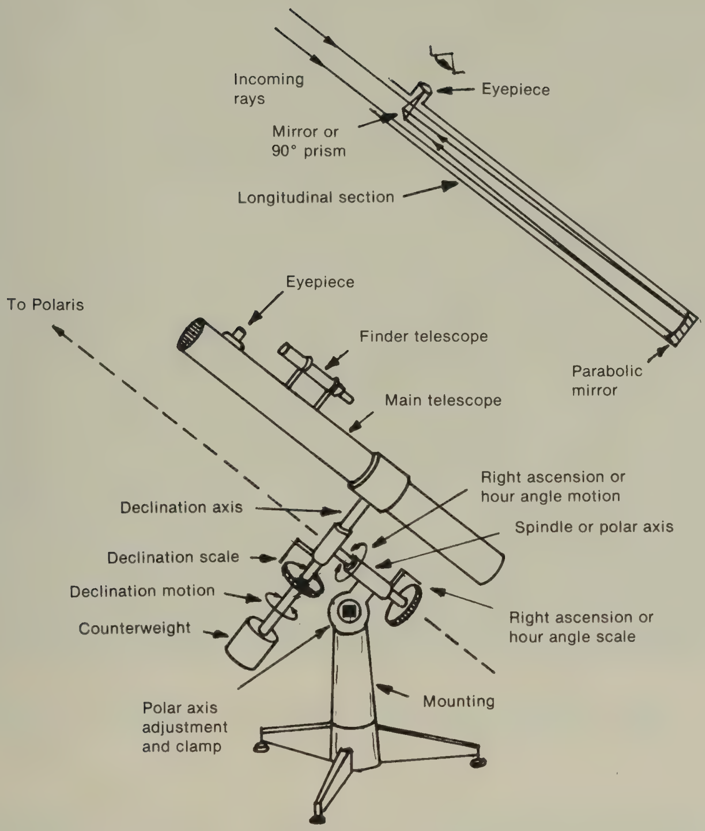
The right ascension of the meridian is the same as the *local sidereal time* (or star time). A celestial object is on the meridian (hour angle zero) when the sidereal time is equal to the object's right ascension. Sidereal time differs from ordinary civil time by about 4 minutes per day (more exactly by 3 minutes 56.6 seconds) because the *sidereal day* is the time it takes the earth to rotate once with respect to the stars while the ordinary or *civil day* is the time it takes to rotate once with respect to the sun. Observatories maintain clocks which give the sidereal time and many amateurs use such clocks. A short wave radio is useful to provide (civil) time signals (in North America from WWV, Boulder, Colorado, on 5, 10 and 15 megahertz or from CHU, Ottawa, Canada, on 7.3 megahertz). Conversion from civil to sidereal time is facilitated by use of tables or a "Star Time Calculator" (Edmund Scientific Co. No. 40399).

A Small Optical Telescope

Even without a telescope at hand the following step-by-step procedure is useful reading because it provides an example of how telescopes are set and how celestial coordinates are employed.

Suppose we are located in the northern hemisphere and wish to observe the object with R.A. = 4 hours and Dec. = 30° N. when the local sidereal time (L.S.T.) is 7 hours. We may proceed as follows:

1. Align the telescope tube with its polar or right ascension axis.
2. With a low power eyepiece in the telescope (or a low power finding telescope attached to the side of the main telescope) adjust the telescope mounting so that the north star (Polaris) is centered in the field of view. This aligns the polar axis with the earth's axis to within about 1°, the distance of Polaris from the north celestial pole. This difference can be corrected but for casual observations may not be necessary.



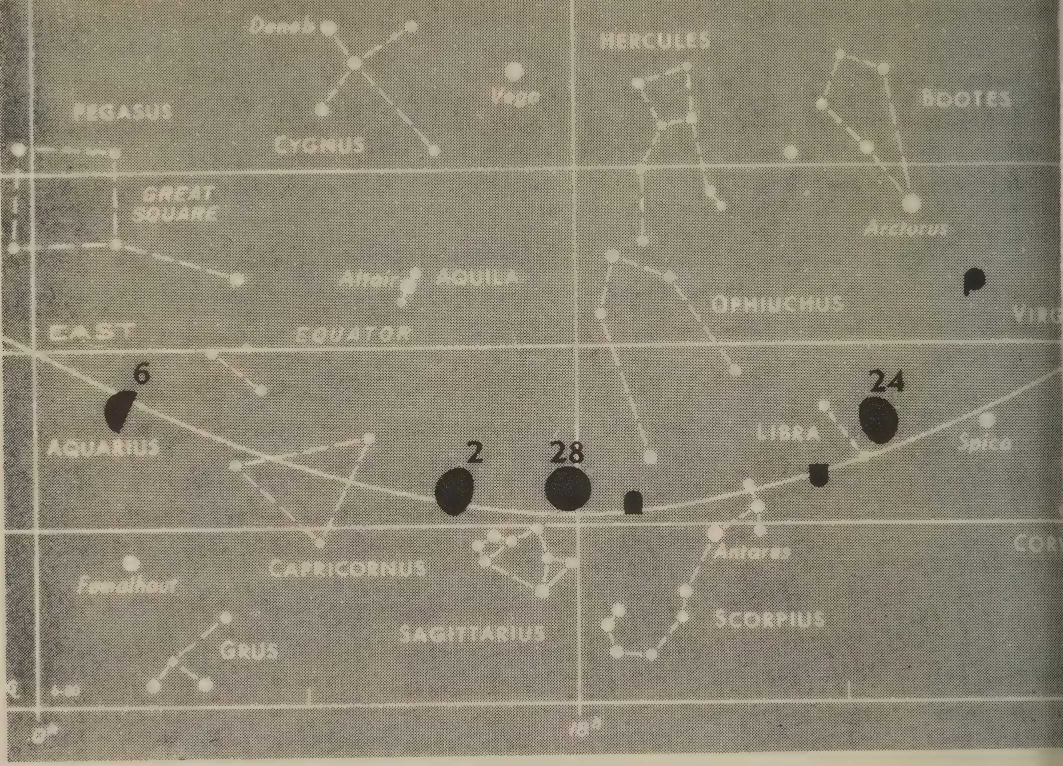
Components of a small equatorially-mounted optical telescope.

3. Turn the telescope on its axis so that it points at a landmark directly to the south (or to the north) and set the hour angle scale on the polar axis to zero. With the polar axis in this position movement in declination swings the telescope along the meridian (at zero hour angle).

4. With the declination scale set to read 90° N. when the telescope is directed at Polaris, swing the telescope to 30° N. declination.

5. Next turn the telescope on its polar axis to an hour angle of +3 hours (or 3 hours west of the meridian). (The right ascension of the object is 4 hours and the local sidereal time is 7 hours. Therefore, H.A. = L.S.T. − R.A. = 7 − 4 = +3 hours).

6. The telescope should now be on or close to the object at R.A. = 4 hours and Dec. = 30° N. but may not be. Noting the configuration of nearby stars in an atlas, use the low power finding telescope (or the main telescope with a low power eyepiece) to locate the object and correct the right ascension and declination settings to center it in the field of view.



Sun, moon and planets for June 1980 (Reproduced by permission

7. Motion only in right ascension, by turning the telescope on its polar axis to compensate for the earth's rotation, should now keep the object in the field of view.

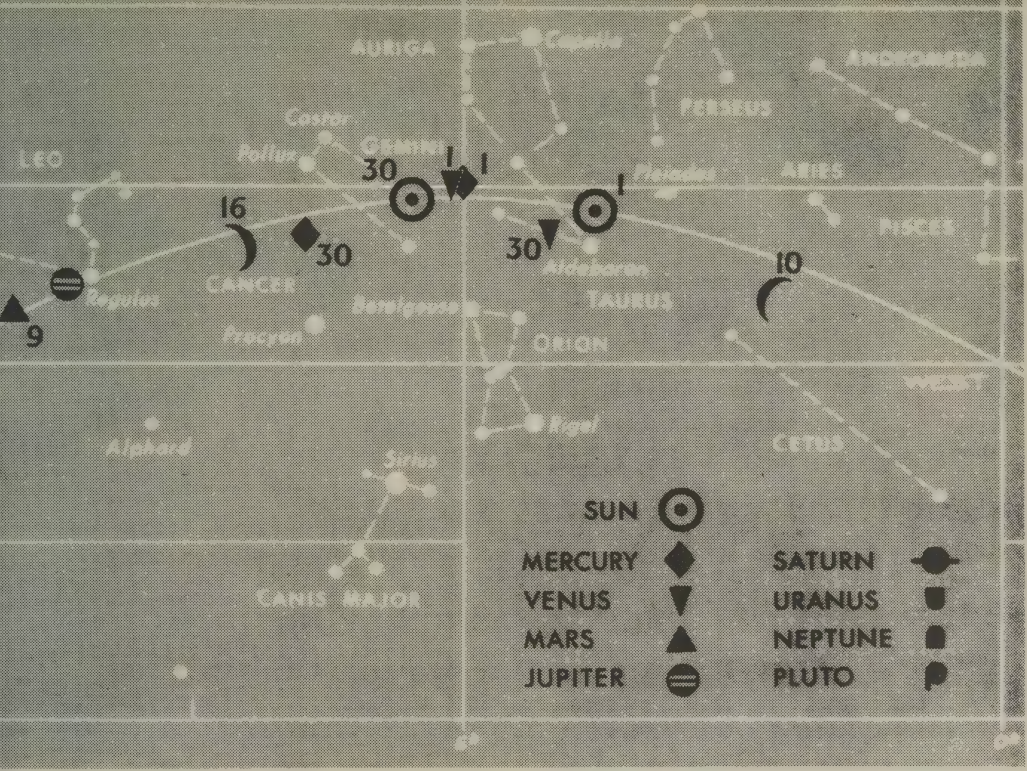
8. Try eyepieces with different magnifications to obtain the most satisfactory one.

9. If the polar axis scale of the telescope has right ascension markings from 0 to 24 hours (instead of hour angle markings of 0 hours plus and minus 12 hours) the settings may be made as follows:

Instead of steps 3, 4 and 5 locate some bright star of known right ascension and the declination. Set the right ascension scale to the star's right ascension and the declination scale to the star's declination. Then swing the telescope to R.A. = 4 hours and Dec. = 30° N. and it should be on the object.

Finding Your Way Around the Sky

To locate and identify planets and stars there are a variety of charts which are helpful. For example, *Sky and Telescope* publishes a monthly star chart showing the stars overhead for evenings of that month. *Sky and Telescope* also publishes a chart for the "Sun, Moon and Planets This Month", and in addition charts showing the positions of the moons of



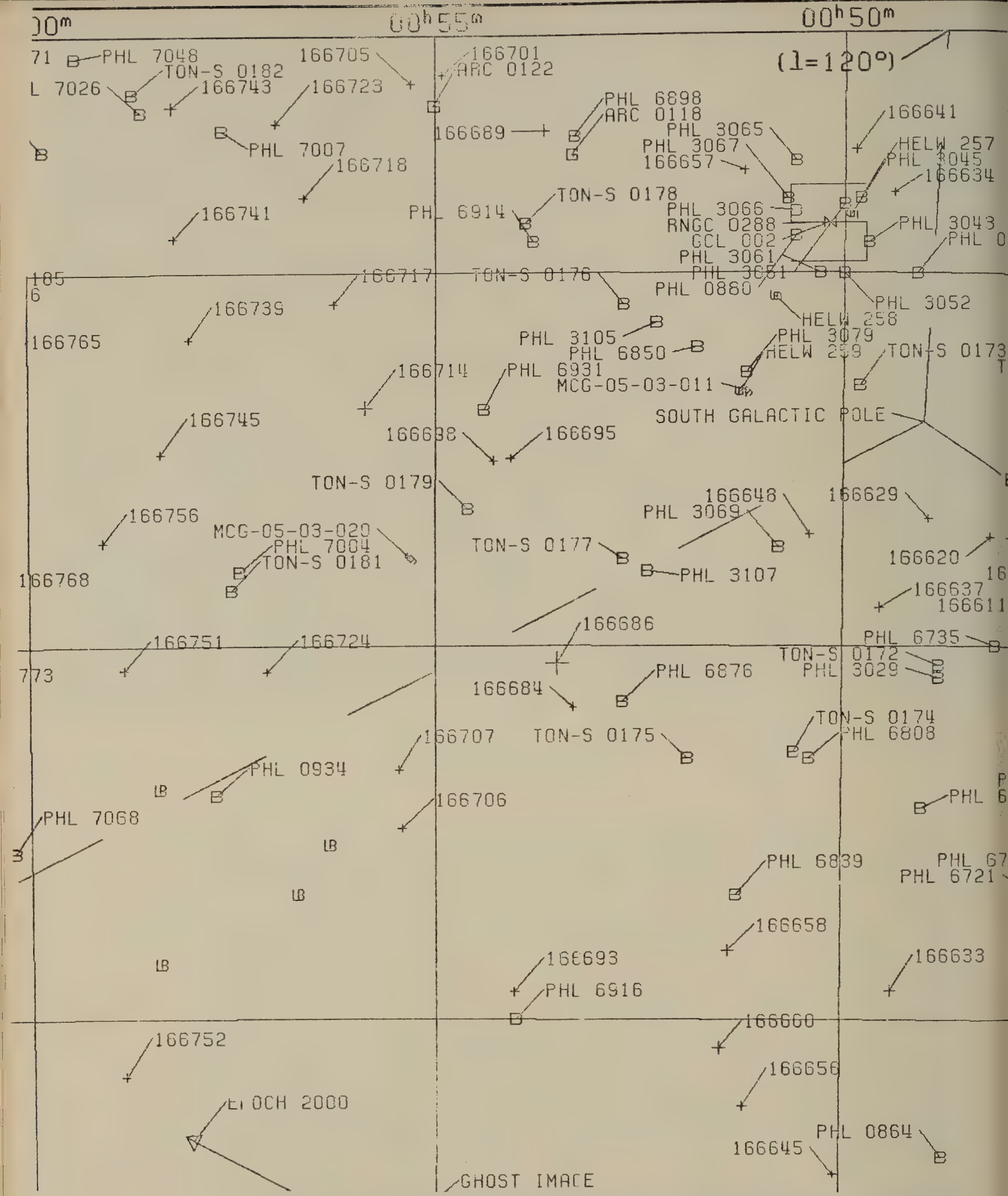
from *Sky and Telescope*, © 1980 Sky Publishing Corp.)

Jupiter and Saturn. A reference for even more detailed position information on the sun, moon and planets is the "American Ephemeris and Nautical Almanac" issued yearly by the U.S. Government Printing Office.

More information on celestial objects may be found in a variety of star atlases such as "Norton's Star Atlas and Reference Handbook" (see references).

But for the most complete and detailed information concerning stars, star clusters, galaxies, galaxy clusters, nebulas, quasars, supernova remnants, and other objects beyond the solar system the Palomar Sky Survey photographs may be used with transparent overlay maps prepared by the Ohio State University Radio Observatory. These transparent overlays permit immediate identification of about one-half million objects on the Palomar Sky Survey photographs. There is a separate overlay for each of the more than 1000 Palomar Sky Survey photographs. The overlay dimensions are the same as the Palomar Sky Survey photographs (36 by 43 centimeters or 14 by 17 inches), each photograph covering about a 6 by 6 degree area of the sky.

For convenience, position and other data for some of the brightest stars and some other objects of interest are listed beginning on page 265.



Sample of overlay for Palomar Sky Survey photograph showing about one-fifth of one map at reduced size. The actual dimensions of the overlays are the same as the Palomar prints (36 x 43 centimeters or 14 by 17 inches).

Explanatory symbol and magnitude tables, including summaries of each type of object on each map, appear at the upper right. This sample includes the South Galactic Pole (left of center, toward top). Above it is a large star cluster (indicated by a large *S*) which contains many blue objects (each indicated by a *B*) with a nebula (indicated by an *N*) at the center.

The overlay maps are made of dimensionally-stable abrasion resis-

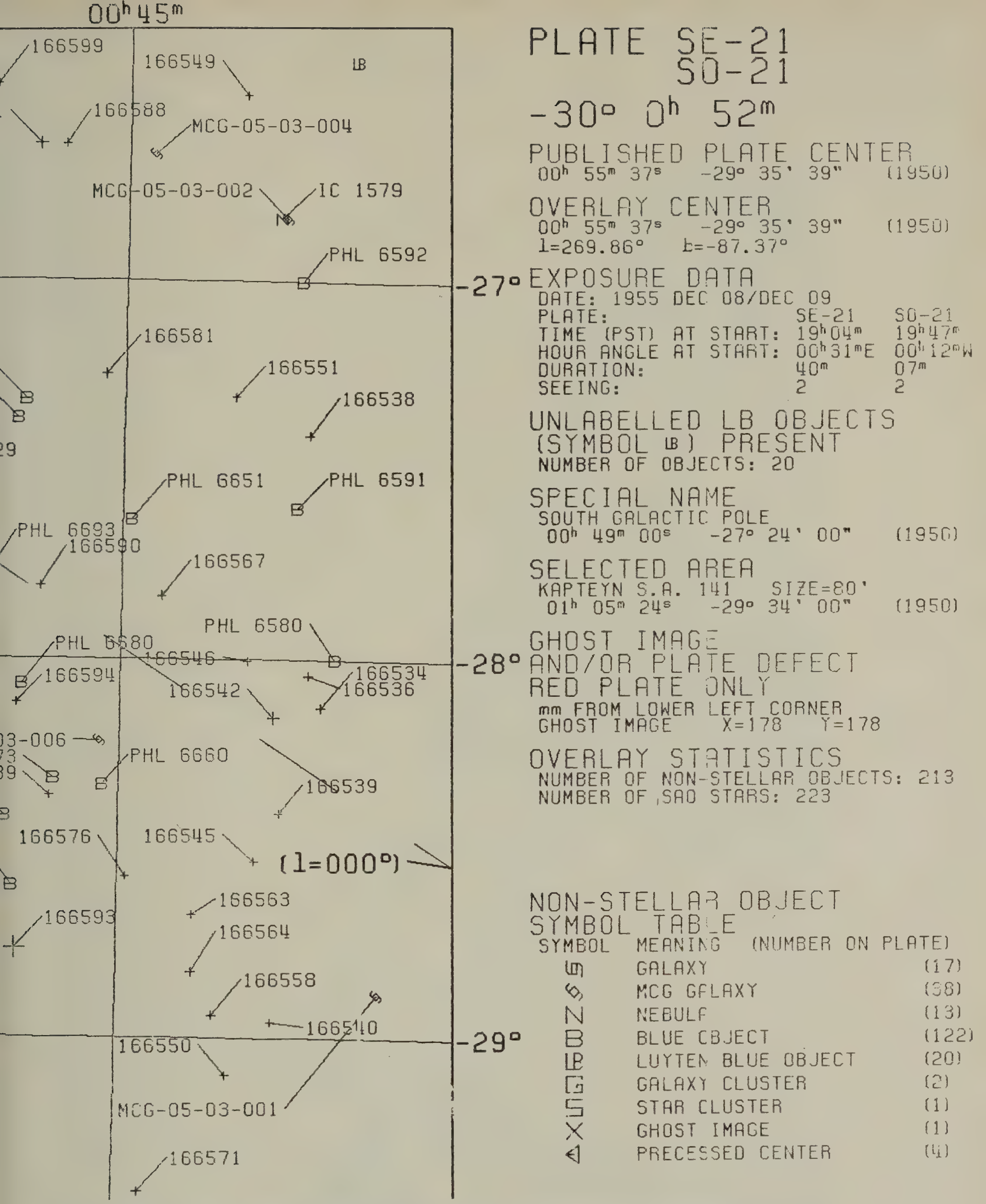


PLATE SE-21
SO-21

-30° 0h 52m

PUBLISHED PLATE CENTER
00h 55m 37s -29° 35' 39" (1950)

OVERLAY CENTER
00h 55m 37s -29° 35' 39" (1950)
l=269.86° b=-87.37°

EXPOSURE DATA
DATE: 1955 DEC 08/DEC 09

	SE-21	SO-21
PLATE:	SE-21	SO-21
TIME (PST) AT START:	19h04m	19h47m
HOUR ANGLE AT START:	00h31mE	00h12mW
DURATION:	40m	07m
SEEING:	2	2

UNLABELLED LB OBJECTS
(SYMBOL LB) PRESENT
NUMBER OF OBJECTS: 20

SPECIAL NAME
SOUTH GALACTIC POLE
00h 49m 00s -27° 24' 00" (1950)

SELECTED AREA
KAPTEYN S.A. 141 SIZE=80'
01h 05m 24s -29° 34' 00" (1950)

GHOST IMAGE
AND/OR PLATE DEFECT
RED PLATE ONLY
mm FROM LOWER LEFT CORNER
GHOST IMAGE X=178 Y=178

OVERLAY STATISTICS
NUMBER OF NON-STELLAR OBJECTS: 213
NUMBER OF SAO STARS: 223

NON-STELLAR OBJECT
SYMBOL TABLE

SYMBOL	MEANING	(NUMBER ON PLATE)
m	GALAXY	(17)
%	MCG GALAXY	(38)
N	NEBULA	(13)
B	BLUE OBJECT	(122)
LB	LUYTEN BLUE OBJECT	(20)
G	GALAXY CLUSTER	(2)
S	STAR CLUSTER	(1)
X	GHOST IMAGE	(1)
◁	PRECESSED CENTER	(4)

tant clear plastic. A user may add his own notations on the overlays with water-soluble ink and wipe them off later with a damp cloth.

An important special feature is that the overlays can be used by themselves as detailed sky maps without the Palomar sky photographs. They may also be used as finding charts by reproducing any desired portion of the overlays. The overlays are accompanied by a text containing complete reference information for all of the objects shown.

Each set contains 1037 overlays, one for each different red print of the Palomar Sky Survey including the Whiteoak southern extension. The overlays have been prepared by Robert S. Dixon, Paul Schmidtke and Mirjana Gearhart of the Ohio State University Radio Observatory.

A Small Radio Telescope

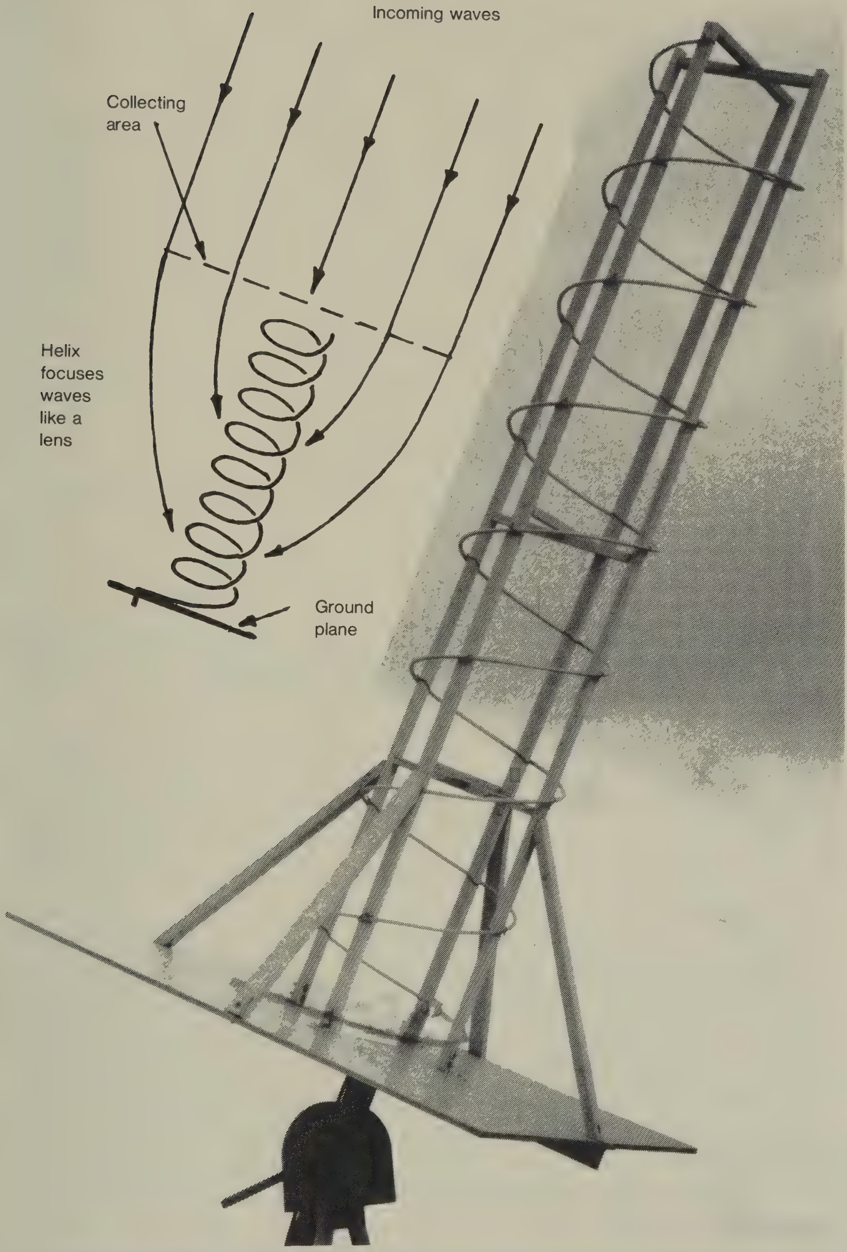
With a radio telescope you can observe anytime day or night, in clear or cloudy weather, and with indoor comfort in all seasons. By running a recorder continuously your telescope can be on the air 24 hours a day scanning the sky and taking data automatically which you can inspect and interpret at your later convenience. You will be exploring a new and different cosmos from the one you can see. With even the simplest radio telescope you may observe things that Jansky and Reber couldn't detect. A simple twin-helix interferometer telescope will be described briefly.

The twin-helix telescope has two helical antennas separated by some convenient distance along an east-west line. The helices can be tilted in the north-south (or declination) direction to point anywhere along the meridian (an imaginary circle in the sky passing through the zenith and the north and south points of the horizon). Both helices are set at the same declination. Normally the helices are fixed at this setting for 24 hours of observations scanning the sky as celestial sources cross (or transit) the meridian from east to west due to the earth's rotation. A wavelength of 1.35 meters was chosen but longer or shorter wavelengths can be used.

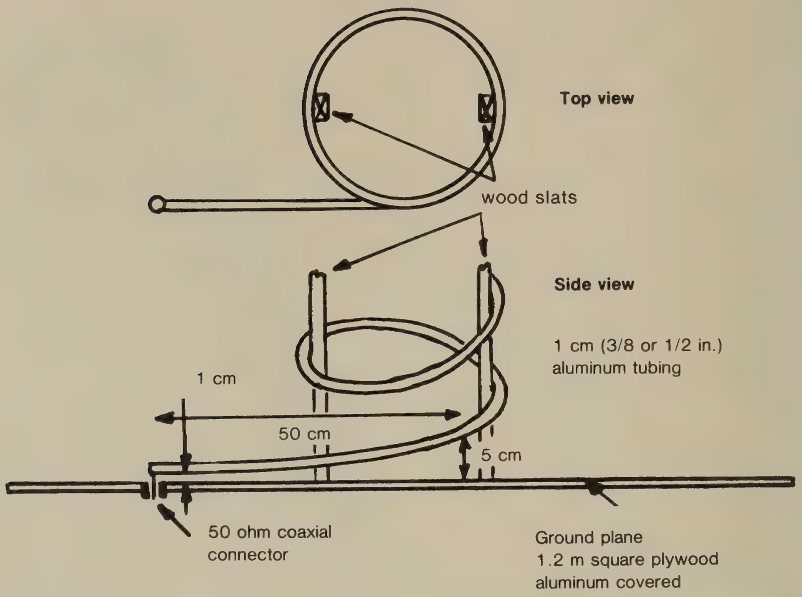
The two helical antennas are connected by a flexible 50-ohm coaxial cable (Type RG-8/U) to a receiver consisting of a number of components (see block diagram). The receiver is connected to a recorder for producing a permanent record. Chart speeds of a few centimeters per hour are satisfactory. An audio amplifier and loudspeaker can also be connected. By listening to the loudspeaker one can tell, when spikes appear on the record, whether they are due to interference from automobiles, radars or radio or TV stations or whether they are genuine solar bursts or radio source scintillation.

Few ready-made radio telescopes or kits are as yet available for amateurs but many types, including the twin-helix one described here, are well within the capabilities of most radio amateurs to construct from components.

Two actual records taken three days apart in November 1974 with the twin-helix telescope at the Ohio State-Ohio Wesleyan Radio Observatory show much of interest. There are interferometer lobes with 32 minute spacing due to Cassiopeia A, lobes with 22 minute spacing due to Cygnus A, lobes with 19 minutes spacing due to the sun and a gradual rise about 3 hours long due to the plane of our galaxy or Milky Way. The antennas were pointed to a declination midway between Cassiopeia A and Cygnus A to favor them but the sun was also detected, even though it was far to the south because it was very strong.



Helical antenna for interferometer radio telescope. The helical antenna is highly directional with maximum response off its open end. It collects radio waves over a large area, focusing them like a lens as suggested in the sketch.

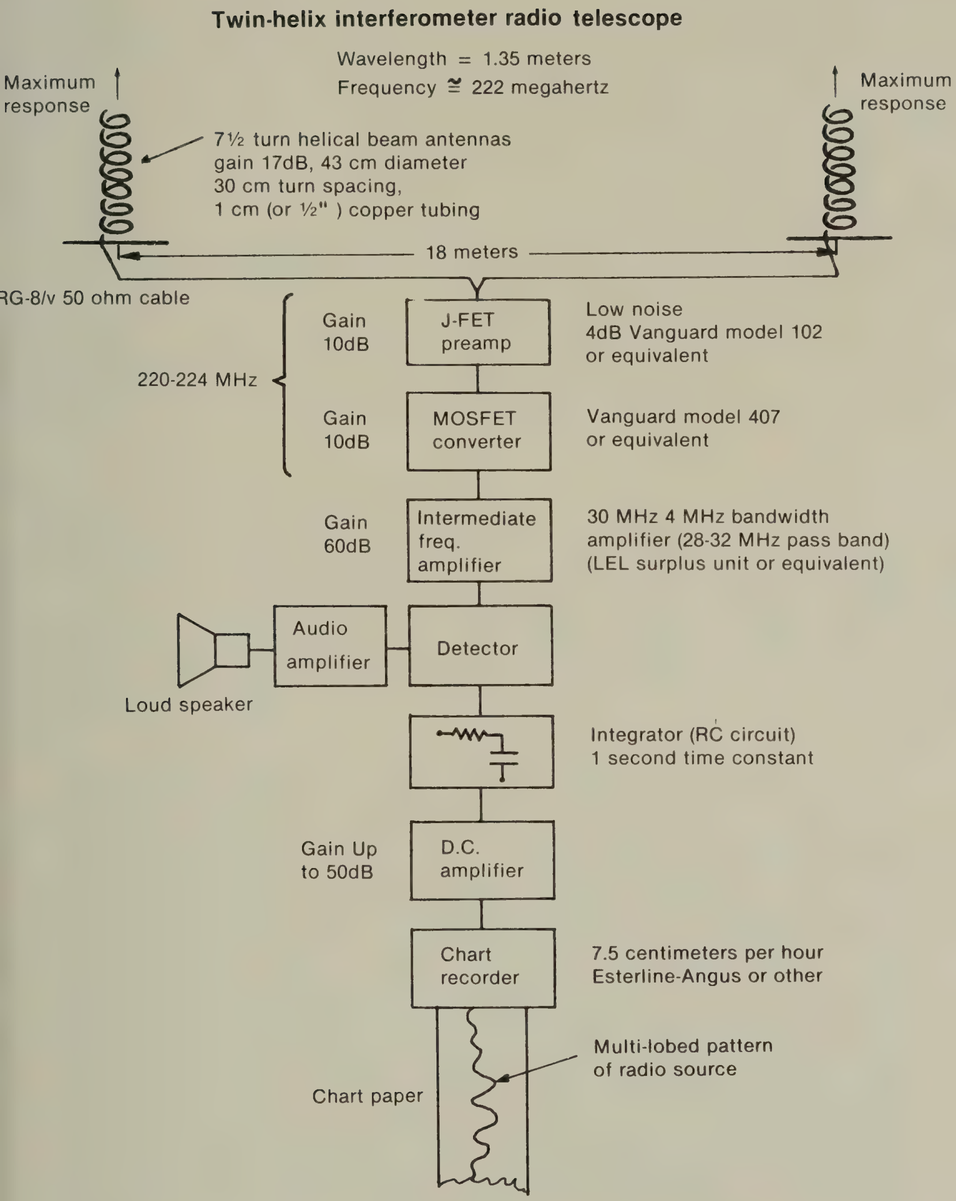


Construction details for helical antenna. The structure supporting the helical conductor is of wood. The ground plane is heavy aluminum foil over a plywood sheet. The impedance is about 50 ohms.

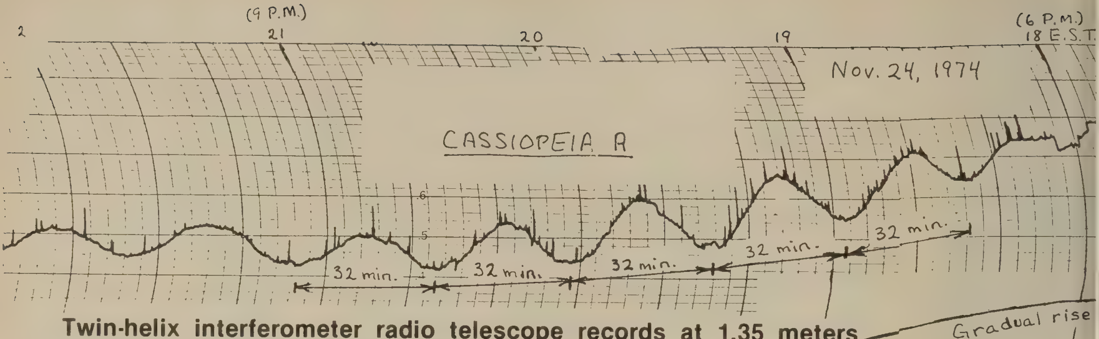
In addition, superimposed on the peaks of the sun lobes are spikes indicating strong bursts due to violent activity associated with sun spots. On the loud speaker, these bursts sound like escaping steam. The bursts start suddenly and die away gradually over seconds or minutes. On the November 21st record around 1335 hours (E.S.T.) there was a very large burst lasting several minutes.

The bursts are caused by flares, particle clouds rising at high velocity through the solar corona from huge explosions near the surface like the mushroom clouds of Hiroshima but many million-fold larger. The bursts and lobes on November 21st are much larger than on November 24th indicating more solar activity on the earlier date. It is to be noted that the true solar bursts appear as spikes on the sides and peaks of the sun lobes and *not* in the valley bottoms or minima where the interferometer response is near zero. Spikes in the valleys would be suggestive of terrestrial interference because the interferometer response to the sun should be small in the valleys.

It is interesting to correlate the solar burst activity observed with a radio telescope to the number and size of sun-spots seen optically. The sun is an erratic, highly variable radio source. It is fortunate that its optical output is not as variable or we would be alternately frozen and fried.



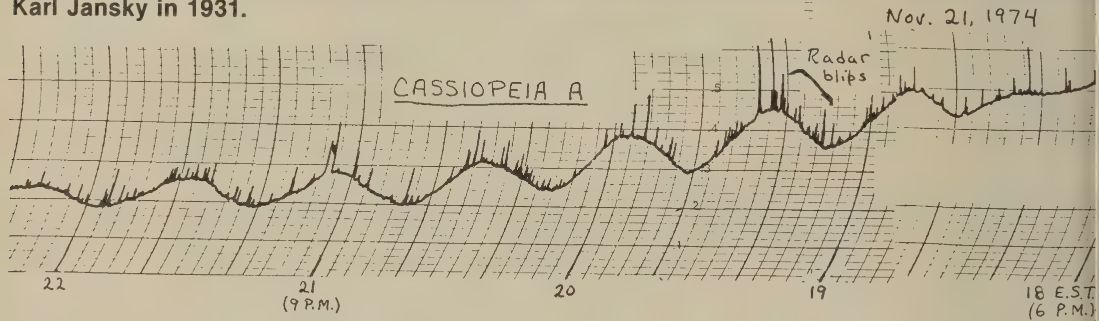
Block diagram of a small radio telescope. This system is only one of many possible arrangements. For example, systems for receiving weather satellite pictures or TV pictures from a geostationary satellite could be modified to work as a radio telescope.



Twin-helix interferometer radio telescope records at 1.35 meters wavelength (222 megahertz). The two records (3 days apart) are displaced 12 minutes for alignment in sidereal time. The standard time-sidereal time difference is 4 approximately minutes per day.

The records show the three strongest radio sources: the sun, Cassiopeia A and Cygnus A, and also a gradual extended rise due to our galaxy (plane of the Milky Way), the latter being the source detected by Karl Jansky in 1931.

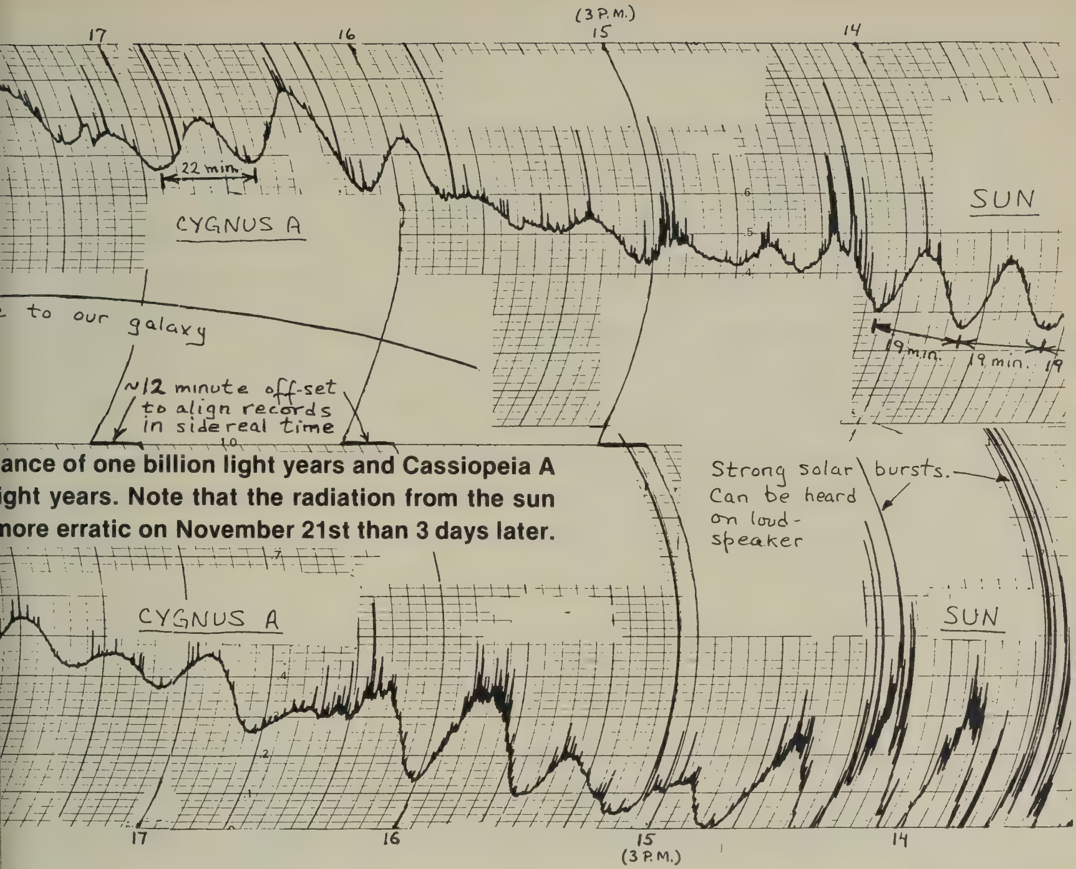
Cygnus A is at a distance of was much strong



Associated with a solar flare is x-ray radiation which can produce a sudden increase in ionization in the earth's ionosphere (D layer) resulting in improved long-distance transmission of long wavelength (6000 meter) radio waves. If a radio receiver in the temperate latitudes is tuned (between radio stations) to a wavelength of 5000 to 7000 meters an increase in background static (atmospherics) will be noted at the onset of a solar flare due to the improved transmission of lightning induced static from tropical thunderstorms. This Sudden Enhancement of Atmospherics (SEA) can be used to set off an alarm so that one can make optical observations of the flare or note the appearance and sounds of bursts on a radio telescope (assumed running continuously).

Late at night on both days there are spikes both on the peaks and in the valleys of the Cassiopeia A lobes. From their musical tone on the loudspeaker and their regular periodicity, about one per minute, they were identified as a distant radar station being received by unusual tropospheric propagation conditions and subject to severe fading or fluctuation in strength from one minute to the next.

If spikes occurred only on the peaks of the Cassiopeia A or Cygnus A lobes and not in the valleys it would suggest scintillation (or twinkling) of



ance of one billion light years and Cassiopeia A ight years. Note that the radiation from the sun nore erratic on November 21st than 3 days later.

the type Antony Hewish was seeking when Jocelyn Bell discovered the first pulsar. Occasionally such scintillation may be observed.

On these records we have four radio sources: our galaxy, Cygnus A, Cassiopeia A and the sun. The rise due to our galaxy is reminiscent of the bump Jansky saw on his records only it is more prominent on ours. The lobes due to Cygnus A and Cassiopeia A on our records are more distinct than the indications Reber obtained, while the solar lobe activity reminds one of what happened in February 1942 when the British at first mistook the sun for a new kind of German radar jammer.

The sun is at a distance of 150 million kilometers (light travel time of 500 seconds). Cassiopeia A is the remnant of an exploded star at a distance for which the radio (and light) travel time is 12 000 years. The galactic rise is due to radiation from energetic electrons permeating the interstellar space of our galaxy and coming from a range of distances which on the average is probably at least as far as Cassiopeia A.

Cygnus A is a double radio source so far away that the radio wave travel time is one billion years. The signals from Cygnus A are true relics of antiquity. Even though Cygnus A is one billion light-years distant it is easily detected by this small radio telescope.

In 1955 Bernard Burke and Kenneth Franklin of the Carnegie Institution of Washington, D.C., discovered strong, fluctuating, erratic radio emission from the planet Jupiter at a wavelength of about 14 meters. The emission is generated by electrons spiralling in the magnetosphere surrounding the planet. The emission is too weak at 1.35 meters wavelength to be detected on the twin-helix radio telescope we have been discussing but using a simple beam antenna (3-element Yagi type) pointed at Jupiter and a standard short-wave receiver (½ microvolt sensitivity) covering the 18 to 22 megahertz (15 meter wavelength) region, a patient listener may be rewarded by hearing the swishing sounds of Jupiter emission. The active times of the Jupiter radiation tend to be controlled by the position of the innermost Galilean satellite Io and it is now possible to calculate and predict when these periods of activity will occur.

The lobe spacing of an interferometer is equal to 57° divided by the separation (S) between antennas in wavelengths. For the twin-helix interferometer the separation is 18 meters so at a wavelength of 1.35 meters S is 18/1.35 = 13.4 wavelengths. Thus, the lobe spacing angle

$$\Theta = 57°/13.4 = 4.3°$$

At the celestial equator (declination = 0°) objects move at the rate of 4 minutes per degree so the lobe spacing should be 4.3 x 4 = 17.2 minutes. The lobe spacing at other declinations (δ) is given by the lobe spacing at 0° declination divided by cosine δ. On November 24 the sun's declination was about −20.5° so:

$$\text{Calculated lobe spacing for sun} = 17.2/[\cos(-20.5°)] = 18.4 \text{ minutes}$$

The measured separation of the lobes near noon was 18.5 minutes which is in satisfactory agreement.

A Radio — Optical Comparison

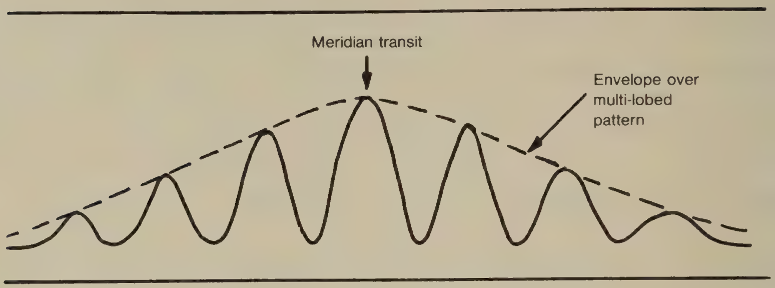
The following table compares the distances of the three strongest radio and optical objects. (Jupiter omitted because of its variability).

Radio		**Optical**	
Object	**Distance**	**Object**	**Distance**
1. Sun	8 light minutes	1. Sun	8 light minutes
2. Cas A	12 000 light years	2. Moon	1 light second
3. Cygnus A	1 billion light years	3. Venus	less than 14 light minutes

Carrying this comparison further, for example, to the 500 strongest radio objects, the majority will be farther than five million light years and some will be at distances of 12 billion light years or more. Thus, radio telescopes provide an immensely deep view of the universe even with a small number of the strongest sources. By contrast, of the 500 brightest optical objects, most will be nearer than one thousand light years.

From the declination of Cygnus A and Cas A (40.6° and 58.5°, respectively) the lobe spacings should be 22.6 and 32.9 minutes. These values compare well with the measured values of 22 and 32 minutes. The data in summary are:

		Lobe Spacing (minutes of time)	
Object	**Declination**	**Calcuated**	**Measured**
Sun	– 20.5	18.4	18.5
Cygnus A	+ 40.6°	22.6	22
Cas A	+ 58.5°	32.9	32



Multi-lobed interferometer pattern. Radio source crosses meridian at maximum of the envelope which encloses the lobe pattern. On the November 24, 1974, record, meridian transits occurred as follows: Cassiopeia A at 1943, Cygnus A at 1620, sun at 1205 (off chart at right).

It is apparent that if we observe an interferometer pattern for a source whose declination (north-south coordinate) is unknown we can calculate its declination from the foregoing relations, while the right ascension (east-west coordinate) can be found by noting the sidereal (star) time at which the envelope of the lobe pattern is largest.

Only our galaxy, seen more or less edge-on, yields a broad gradual response free of interferometer lobes. This is because it is many degrees wide (several times the 4.3° lobe width of the interferometer). Cassiopeia A and Cygnus A are a small fraction of a degree. The sun is about one-half degree in extent. Thus, these three objects are all small compared to the interferometer lobe width of 4.3° so they produce a readily recognizable multi-lobed pattern. This illustrates the advantage of the two-helix interferometer over a single helix. With a single helix the sun, Cassiopeia A and Cygnus A would all produce broad gradual patterns like that for our galaxy and it would be difficult to detect them. The beam width of the individual helix is 40° making a single helix pattern at least 40 x 4 = 160 minutes wide in time. A pattern of this width is more difficult to recognize and interpret than the multi-lobed ones.

Even with severe interference the radio sources Cygnus A and Cassiopeia A can be recorded provided there are periods of a few seconds every minute or so when the interference is absent. At these times the recorder pen or stylus drops to the true sky level and the multi-lobed pattern can be seen *under* the interference.

Whereas optical astronomers express the brightness of a star by its magnitude, radio astronomers express the "brightness" of a radio source directly in the basic physical quantities involved, namely the power received (watts) per unit area (square meters) per unit of bandwidth (hertz). This quantity if called the *flux density* and the unit employed is the jansky (abbreviated Jy) after Karl G. Jansky, the radio astronomy pioneer, where 1 jansky = 10^{-26} watts per square meter per hertz. The basic physical quantities for the optical magnitude are power per unit area (watts per square meter). For example, for a star of zero magnitude a visual observer detects a total power of the order of a 10^{-8} watts per square meter. More explicity magnitudes determined by a visual observer are called *visual magnitudes* which may differ from magnitudes determined photographically, called *photographic magnitudes,* because of the difference in sensitivity of the eye and photographic plate to various parts of the optical spectrum.

The flux densities of a few radio sources are listed on page 269.

The Atoms in the Observable Universe

Object	Number
Sugars	10^2
DNA	10^5
Virus	10^8
Bacterium	10^{14}
Glass of water	10^{25}
Man	10^{27}
Earth	10^{51}
Sun	10^{57}
Galaxy	10^{68}
Universe	10^{79}

There are approximately 10^{25} (10 trillion trillion) molecules of water in a glass. To illustrate the immensity of this number suppose that each molecule could be marked and the glass then dumped in the ocean. If, after the glass of water was thoroughly stirred among the seven seas, then another glass, any glass, taken from an ocean anywhere in the world, would contain over 1000 of the marked molecules from the original glass. Would-be polluters take note.

Across the Universe at the Speed of Light

	Light travel time
Across atomic nucleus	1 micro atto second
Across a virus	100 attoseconds
Across a bacterium	1 femtosecond
1 meter	3 nanoseconds
New York to London	0.02 second
Around the earth	0.13 second
Earth to moon	1.3 second
Earth to sun	500 seconds = 8.3 minutes
Earth to Venus (minimum)	2.3 minutes
Earth to Venus (maximum)	14 minutes
Earth to Mars (minimum)	2.8 minutes
Earth to Mars (maximum)	21 minutes
Sun to Pluto	5.5 hours
Diameter of solar system	11 hours
Sun to nearest star	4 years
Sun to center of galaxy	30 000 years
Diameter of galaxy	100 000 years
Distance to Andromeda galaxy	2 million years
Distance to Cygnus A	1 billion years
Distance to quasar OQ172	14 billion years
Distance to observable limit	15 billion years

ELEMENTARY PARTICLES

Mass and Charge of Some Elementary Particles in Terms of the Mass and Charge of the Electron

Family Name	Particle	Mass	Charge	Lifetime (seconds)
	Electron	1	– 1	∞
	Positron	1	+ 1	∞
Leptons	Neutrino	approx. 0	0	∞
	Negative muon	207	– 1	2×10^{-6}
	Positive muon	207	+ 1	2×10^{-6}
	Pi meson	273	± 1	2×10^{-8}
	Pi meson	264	0	2×10^{-16}
Hadrons	K meson	967	± 1	10^{-8}
	K meson	974	0	10^{-10}
	Proton	1836	+ 1	∞
	Antiproton	1836	– 1	∞
	Neutron	1838	0	10^{3}
Baryons	Sigma hyperon	2328	± 1	10^{-10}
	Xi hyperon	2580	∓1	10^{-10}
	Deuteron (heavy hydrogen nucleus)	3666	+ 1	∞
	Alpha particle (helium nucleus)	7294	+ 2	∞

Mass of electron = 9.11×10^{-31} kilograms

Charge of electron = -1.602×10^{-19} coulombs

UNITS AND PREFIXES

Numerical value	Prefix	Pronunciation	Symbol	As used in this book (U.S.A. meaning)	Meaning in other other countries
1 000 000 000 000 000 000 = 10^{18}	exa	(ex a)	E	one quintillion	trillion
1 000 000 000 000 000 = 10^{15}	peta	(pet a)	P	one quadrillion	thousand billion
1 000 000 000 000 = 10^{12}	tera	(tare a)	T	one trillion	billion
1 000 000 000 = 10^{9}	giga	(jig a)	G	one billion	milliard
1 000 000 = 10^{6}	mega	(meg a)	M	one million	
1 000 = 10^{3}	kilo	(kill o)	k	one thousand	
100 = 10^{2}	hecto	(hek toe)	h	one hundred	
10 = 10	deka	(dek a)	da	ten	
0.1 = 10^{-1}	deci	(dec i)	d	one tenth	
0.01 = 10^{-2}	centi	(cent i)	c	one hundredth	
0.001 = 10^{-3}	milli	(mill i)	m	one thousandth	
0.000 001 = 10^{-6}	micro	(my kro)	μ	one millionth	
0.000 000 001 = 10^{-9}	nano	(nan o)	n	one billionth	milliardth
0.000 000 000 001 = 10^{-12}	pico	(pee ko)	p	one trillionth	billionth
0.000 000 000 000 001 = 10^{-15}	femto	(fem toe)	f	one quadrillionth	thousand billionth
0.000 000 000 000 000 001 = 10^{-18}	atto	(at o)	a	one quintillionth	trillionth

Example: 1 kilometer = 1000 meters; 1 micrometer = one millionth of a meter
Conversion: 1 meter = 39.37 U.S. inches = 40 inches (nominal)

Temperature unit: degree celsius (°C)
Temperature above absolute zero: kelvin (K)

Absolute zero = 0 kelvin = –273.2° celsius = –459.7° Fahrenheit
Freezing water = 273.2 kelvins = 0° celsius = 32° Fahrenheit
Boiling water = 373.2 kelvins = 100° celsius = 212° Fahrenheit

Note: One kelvin equals one degree celsius above absolute zero. Thus, a temperature of 10 degrees celsius above absolute zero is 10 kelvins. With kelvins the word degree is not necessary.

1 astronomical unit = distance earth to sun (500 light-seconds)
1 light year = 9.5×10^{12} kilometers

The Power of Astronomical Objects

Object	Optical (watts)	Radio (watts)
Earth*	6×10^{15}	10^{9}
Jupiter	4×10^{17}	10^{11}
Sun	4×10^{26}	10^{12}
Supergiant	10^{31}	?
White dwarf star	10^{25}	?
Flare star	10^{25}	10^{16} (peak)
Supernova remnant cloud	10^{29}	10^{28}
Pulsar	10^{23}	10^{22}
Normal galaxy (M31) (10^{11} solar masses)	10^{37}	10^{30} to 10^{32}
Radio galaxy (Cygnus A)	10^{35} to 10^{39}	
Quasar	10^{39}	10^{37} to 10^{39}
Black hole (massive)**	0	0

* Earth's optical power radiated is by reflection from the sun. Radio power is generated above ionosphere at 1500 meter wavelengths.

** A massive black hole (3 solar masses or more) does not radiate significantly but matter falling in produces x-rays in the vicinity. On the other hand, a small (mini) black hole (10^{9} tons) does radiate gamma rays like a high-temperature black body in the amount of 10^{9} watts.

An infra-red (young) star may radiate 10^{25} to 10^{26} watts in the infra-red.

TABLE OF TELESCOPE RESOLUTIONS

	Telescope	Aperture or spacing	Wavelength	Resolution (seconds of arc)	Date
OPTICAL	Human eye	3 mm	500 nm	36	
	Galileo's telescope	56 mm	500 nm	2	1610
	Herschel's telescope	1.2 m	500 nm	0.1	1789
	Yerkes Observatory	1 m	500 nm	0.11	1897
	Mt. Palomar	5 m	500 nm	0.022	1948
	Mt. Pastukhova	6 m	500 nm	0.018	1976
	Narrabri interferometer	188 m	500 nm	0.0006	1965
RADIO	Jansky's telescope	30 m	15 m	108 000 (= 30°)	1931
	Reber's telescope	9 m	1.87 m	45 000 (= 12.5°)	1939
	Ohio State University 96-helix telescope	49 m	1.2 m	5 400 (= 1.5°)	1952
	Parkes, Australia	64 m	110 mm	370 (= 0.1°)	1965
	Ohio State University	110 m	110 mm	215 (= 0.06°)	1969
	Molonglo, Australia	1.6 km	735 mm	100 (= 0.028°)	1972
	Arecibo, Puerto Rico	152 m	60 mm	85 (= 0.024°)	1976
	Bonn, Germany	100 m	17 mm	36	1973
	RATAN-600, U.S.S.R.	600 m	30 mm	11	1977
	Gorki, U.S.S.R.	25 m	1 mm	9	1975
	Cambridge, England	5 km	30 mm	1.3	1973
	VLA, New Mexico	27 km	30 mm	0.24	1980
	VLBA (earth's diameter)	12 Mm	30 mm	0.0005	1975
X-RAY	UHURU		5 nm	1800 (= 0.5°)	1970
	Einstein Orbiting Telescope	58 cm	5 nm	4	1979

TABLE OF ASTRONOMICAL OBJECTS

Planets, Stars, Pulsars, Galaxies, Nebulas, Supernova Remnants, Quasars, Blackholes

Planets and largest asteroids		**Average distance from sun**				
		10^6 kilometers	**Light time**	**Average diameter (10^3 km)**	**Sidereal period**	**Length of day**
Mercury		57.9	193 sec	5	88 days	88 days
Venus		108.3	362 sec	12.4	225 days	250 days
Earth		149.7	499 sec	12.7	365 days	1 day
Mars		228.1	761 sec	6.9	687 days	1 day 37 min.
Vesta		354	20 min.	0.4	3.6 years	5 hrs 20 min
Juno	Asteroids or	391	22 min	0.2	4.4 years	7 hrs 13 min
Pallas	minor planets	410	23 min	0.5	4.6 years	
Ceres		415	23 min	0.8	4.6 years	9 hrs 5 min
Jupiter		778.7	43 min	139.8	11.9 yrs	9 hrs 55 min
Saturn		1427.7	79 min	115.1	29.5 yrs	10 hrs 38 min
Uranus		2872.4	2.7 hours	51	84 years	10 hrs 42 min
Neptune		4500.8	4.2 hours	50	165 years	15 hrs 48 min
Pluto		5914.8	5.5 hours	13?	248 years	?

The distance given for the planets from the sun is an average since the planetary orbits are elliptical. However, in the case of a few planets, such as Venus and the earth, the departure of the orbit from circular is quite small.

Moon of earth: Average distance from earth, 384 megameters or 1.28 sec light time.
Average diameter 3480 kilometers.

Four largest moons of Jupiter (discovered by Galileo):

Number	**Name**	**Average distance from Jupiter (10^3 km)**	**Average diameter (km)**	**Sidereal Period**		
				Hours	**Days**	**Minutes**
1	Io	422	3730	1	18	27
2	Europa	671	3150	3	13	13
3	Ganymede	1071	5150	7	3	42
4	Callisto	1884	5180	16	16	32

Sun: Average diameter 1.39 gigameters, Average distance 149.6 gigameters, mass 1.99 x 10^{30} kilograms, power output (See page 263).

SOME OF THE BRIGHTEST STARS

	Position (Epoch 2000.0)				
Name	**Right ascension**	**Declination**	**Distance (light years)**	**Optical power output (sun output = 1)**	**Magnitude**
Alpha Centauri A	$14^h 40^m$	−60°.6	4.3	1.3	0
Sirius A	6 45	−16.7	8.7	23	−1.4
Procyon	7 39	5.4	11.3	6.7	0.4
Vega	18 37	38.8	26	50	0.0
Arturus	14 17	19.2	36	100	−0.1
Capella	5 17	46.0	45	75	0.1
Betelgeuse (red giant)	5 55	7.4	500	13000	0.4
Rigel (supergiant)	5 15	−8.2	900	50000	0.1
Deneb (supergiant)	20 41	45.3	1600	50000	1.3

SUPERNOVA REMNANTS

Name	**Distance (light years)**	**Age (years as of 1975)**	**Diameter (light years)**
Cassiopeia A	11 000	275?	13
Crab nebula (M 1) (1054 A.D.)	3 500	921	
Cygnus loop	2 500	50 000	130
Tycho Brahe's (1572 A.D.)	1 200	403	
Kepler's (1604 A.D.)	3 260	371	

PULSARS

Initial four discovered at Cambridge University, England:

Number	Pulse Period (seconds)	Pulse rate (number per second)	Relative strength at 3.7 meters wavelength
1919	1.337	0.748	1
0834	1.274	0.785	0.5
1133	1.188	0.842	1.2
0950	0.253	3.95	4
Others:			
0531 (Crab nebula)	0.033	30	
0834 (Vela nebula)	0.089	11.2	
2046	1.961	0.51	

BLACK HOLES

Scorpio X-1

Cygnus X-1

Primoridal

NEBULAS
(Gas clouds in our galaxy

Name	Distance (light-years)	Flux density (janskys)
Orion (M 42)	1630	500
Omega (M 17)	5500	1000
Lagoon (M 8)	3900	250
Cygnus X	3250	5000
North America	2900	550

GALAXIES (NORMAL)*

Name	Distance (Millions of light-years)
Small Magellanic cloud	0.165
Large Magellanic cloud	0.165
Andromeda (M 31) (spiral)	2
M 33 (Spiral)	2.3
M 101 (Spiral)	11

* Our galaxy or Milky Way system is a normal galaxy with 10^{11} stars and 100 000 light year diameter. Radio source at center is Sagittarius A, distance 30 000 light-years.

GALAXIES (RADIO)

Name	Redshift (z)	Distance (Millions of light-years)	Diameter (Thousands of light-years)
Cygnus A (double)	0.06	900	400
Centaurus A (double-double)		25	1000
3C295 (double)	0.46	5400	150

QUASARS

Name	Redshift (z)	Distance (Millions of light-years)
3C273	0.16	2 200
3C48	0.37	4 500
OV591	1.22	9 900
OI318	1.62	11 100
OX161	2.42	12 600
4C05.34	2.88	13 100
OH471	3.40	13 500
OQ172	3.53	13 600

SOME RADIO SOURCES

	Position (Epoch 2000.0)			
Source	Right ascension	Declination	Flux density (janskys)	Wavelength
Sun	On ecliptic		100 000 to 100 000 000 (variable) 10 000 000	1.35 m 1 cm
Cassiopeia A (supernova remnant)	23^h23^m	58.7°	9000 2400	1.35 m 21 cm (1420 MHz)
Cygnus A (exploded galaxy)	20 00	40.7	7500 1500	1.35 m 21 cm
Centaurus A	13 25	– 43.0	7000 2000	1.35 m 21 cm
Sagittarius A (galactic nucleus)	17 46	– 28.8	3700 1800	1.35 m 31 cm
Taurus A (M 1) (Crab nebula)	05 35	22.0	1200 1000	1.35 m 21 cm
Virgo A (M 87)	12 31	12.4	900 200	1.35 m 21 cm
3C273 (quasar)	12 29	02.0	70 50	1.35 m 21 cm
OH471 (quasar)	06 47	44.9	0.2 2.0	1.35 m 21 cm
#OQ172 (quasar)	14 45	10.4	1.0 2.5	1.35 m 21 cm

# Most distant known object.

Since the flux density depends, in general, on the frequency or wavelength, the wavelength is listed for each flux density. One of the wavelengths is 1.35 meters, the wavelength used with the twin-helix telescope described above.

Abbreviations: m = meters, cm = centimeters, MHz = megahertz, ^{h} = hours, ^{m} = minutes.

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"COSMIC SEARCH", a magazine about space, the future and the search for intelligent life beyond the earth presented in a popular but responsible manner. COSMIC SEARCH, P.O. Box 293, Delaware, OH 43015.

"Mercury", popular articles on astronomical topics. Astronomical Society of the Pacific, 1244 Noriega St., San Francisco, CA 94122.

"Science News", concise popular articles on all scientific topics with many on space and astronomy. Science Service, 1719 N St. N.W., Washington, DC 20036. Weekly.

"Sky and Telescope", popular articles for amateur and professionl astronomers. Includes star and planetary charts, configurations of Jupiter's moons, etc. Sky Publishing Corp., 50 Bay State Road, Cambridge, MA 02138. Contained a series of articles by George Swenson on how to build an amateur radiotelescope in first 6 issues of 1979.

"Star and Sky", popular articles on astronomy. Star and Sky, P.O. Box 5172, Westport, CT 06880.

Star Time Calculator

A slide rule for converting from standard time to sidereal (star) time or vice versa. Catalog number 40399, Edmund Scientific Co., Barrington, NJ 08007.

Solar Flare Alarm

A Sudden Enhancement of Atmospherics (SEA) receiver (45 kilohertz) with alarm for solar flares. Bob's Electronic Service, 817 N. Andrews Ave., Ft. Lauderdale, FL 33311.

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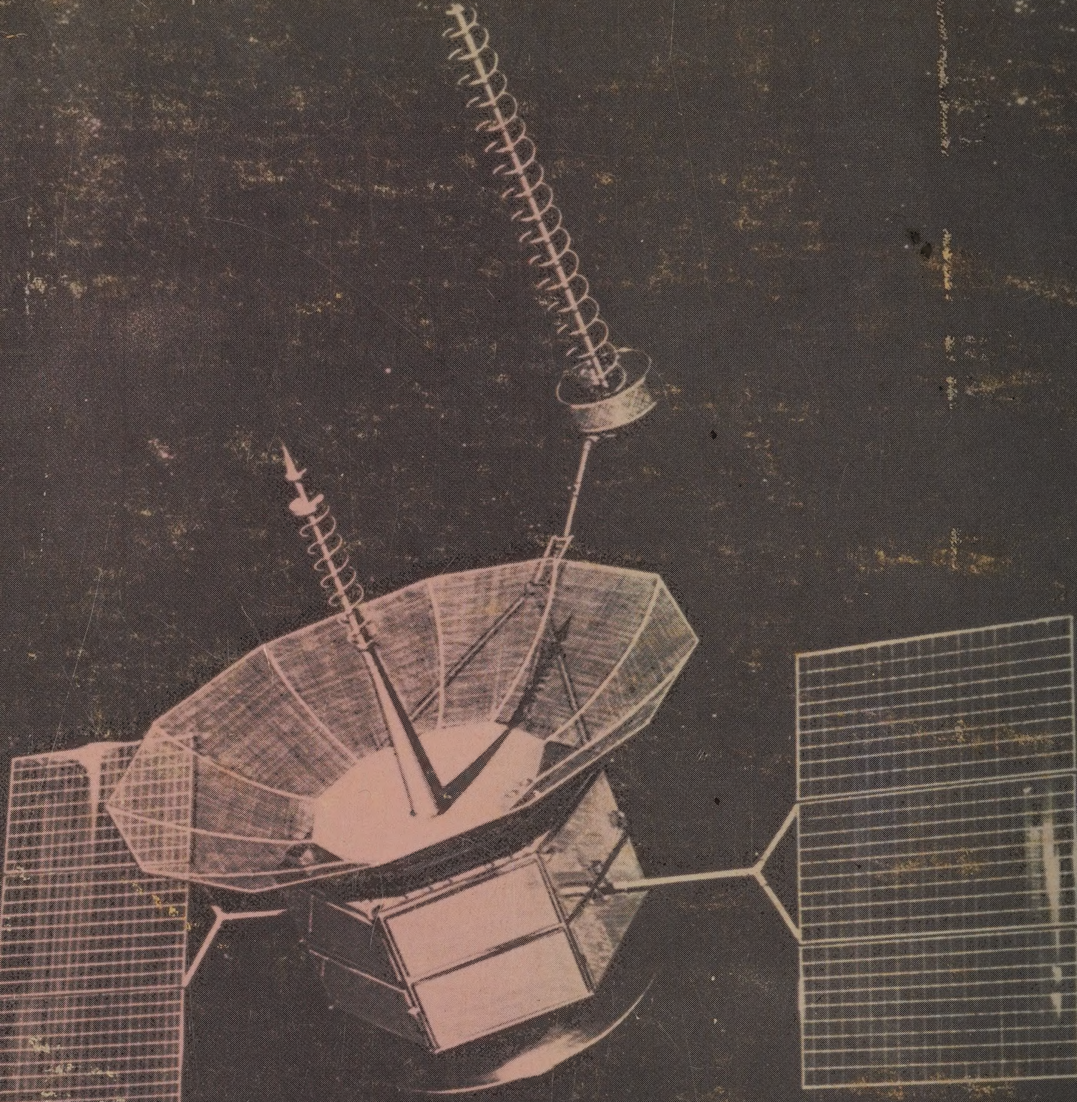

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